2003-039-en

Öko-Institut e.V.
Institut für angewandte Ökologie
Institute for Applied Ecology

Recovery Options for Plastic Parts from End-of-Life Vehicles: an Eco-Efficiency Assessment

Final Report

Darmstadt, May 2003

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for

APME, Brussels

Darmstadt, 12th May 2003

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Institut für Angewandte Ökologie • Institute for Applied Ecology • Institut d'écologie appliquée

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Final Report

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1 Executive Summary

The new European End-of-Life-Vehicles (ELV) Directive 2000/53/EC defines specific recovery, reuse and recycling targets for cars.

In an eco-efficiency study, the Öko-Institut in Darmstadt/Germany analysed and evaluated the recycling and recovery options*1) for seven different plastic components from ELVs (weights ranging from 0.27 kg up to 3.14 kg). The study intends to provide a transparent evaluation tool for the various technology options in terms of environmental impact and corresponding costs in a first step, based on existing data, completed by expert judgement, involving the inherent limitations of a first approach. The results are displayed in eco-efficiency portfolios.

The background data and the resulting portfolios were reviewed by a panel of independent peers (see critical review report in chapter 9). The study was commissioned by the Association of Plastics Manufactures in Europe (APME).

General conclusions:

- Landfill shows the worst eco-efficiency performance in comparison with the other recovery options.
- The eco-efficiency ratings for recovery technologies such as blast furnace, syngas production (SVZ-technology), cement kiln and in some cases to a lesser extend for waste combustion are generally on a comparable level.
- Mechanical recycling can only compete with other recovery technologies when large, easily accessible, monomaterial plastic parts are included.
- Assuming an optimistic 1 to 1 substitution of virgin plastic in an application by recyclate, the purely environmental perspective shows advantages for mechanical recycling compared to the other recovery technologies. From an eco-efficiency perspective, in most cases mechanical recycling is similar to the other options.
- The dismantling costs are the major determining factor for eco-efficiency performance of mechanical recycling.
- An increase in car weight e.g. due to the reduced performance of recycled materials compared to virgin plastics is counterproductive. This is because a lower performing recycled material requires additional material weight and consequently the fuel consumption during the use phase increases.
- Energy saving during the use phase should be given a higher priority. An analysis assessing the relevance of the recovery phase compared to the

whole life cycle (production, use, recovery) of the car indicates that energy consumption (a key indicator) is dominated by the use phase.

Detailed conclusions for mechanical recycling (by analysed part) *2):

- **Bumper:** When the recyclate is directly processed, mechanical recycling represents the most eco-efficient option. The dismantling costs are low as the plastic part is easily accessible. The real market scenario***2)** leads to equivalent eco-efficiency of mechanical recycling with gasification, cement kiln or blast furnace technology.
- **Air intake manifold:** Assuming minimum dismantling costs, the eco-efficiency of mechanical recycling scores slightly better than all other treatment options, but drops significantly when the dismantling time increases.
- **Seat cushion:** Mechanical recycling shows the worst eco-efficiency of all the treatments options. The environmental score is low. Due to the higher density of the foam made from recyclate, mechanical recycling results in high costs (dismantling, cleaning) and negative environmental performance (high weight = higher fuel consumption).
- **Airduct:** Mechanical recycling shows the worst eco-efficiency. Only the pure environmental score of the base scenario is equivalent to all other recovery technologies. The high dismantling costs of this small, hidden part determine the eco-efficiency rating.
- **Mirror housing:** The eco-efficiency score for mechanical recycling of even easily accessible mirror housings is lower than the other treatment options. Parts with a complex design exhibit by far the worst eco-efficiency for mechanical recycling.
- **Wash-liquid tank:** The eco-efficiency of mechanical recycling of this low weight part is nearly in the same order as other treatment technologies. The tank is easily accessible. Mechanical recycling shows good environmental performance but high costs.
- **Headlamp lens:** The mechanical recycling of plastic headlamp lenses shows poor eco-efficiency due to high dismantling costs. Although the environmental score is slightly better, all other options exhibit a better eco-efficiency performance than mechanical recycling.

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*1) The following options were assessed: Landfill, mechanical recycling, co-combustion, feedstock recycling (syngas production, blast furnace), cement production.

*2) The study base case assumes an ideal waste stream with no market restrictions. In the mechanical recycling scenario, recyclate substitutes virgin plastic material completely (1/1 substitution). Practical experience shows that under real market conditions this substitution factor cannot be achieved.

2 Extended Summary

2.1 Background

Throughout Western Europe the recovery of End-of-Life-Vehicles (ELVs) is subject to new legislation. The new European ELV Directive 2000/53/EC defines recovery, reuse and recycling targets by weight for vehicles.

The traditional recovery routes for ELVs are metal oriented. The majority of the other materials are landfilled since currently this still represents the most economic solution.

Achievement of the ELV Directive targets will demand that non-metal fractions are also recovered/recycled. Different recovery routes will therefore be needed. From a technological viewpoint, for the plastics fraction there exist four main options involving six feasible technologies:

- **Mechanical recycling:** The dismantling[1] of plastic parts and subsequent mechanical recycling represent one possible scenario. The recyclate would then substitute virgin material (closed or open loop).
- **Feedstock recycling:** Pre-treated shredder residue can be processed in feedstock recycling processes such as blast furnaces or syngas production.
- **Energy Recovery:** After shredding the ELV and separating the metals, the shredder residue contains most of the plastics fraction. This share can either be used as a fuel substitute in cement kilns after pre-treatment, or directly in municipal waste combustion in order to recover the energy content.
- **Landfill:** Evaluated for comparison reasons only. From the viewpoint of resource efficiency, landfill does not represent a viable option and will be banned for shredded residue.

2.2 General objectives

The aim of the study was to provide a transparent evaluation tool for the recovery technology options in terms of environmental benefits and corresponding costs based on seven different plastic parts from automotive applications.

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[1] New developments are under study to substitute the dismantling step.

Various environmental impact factors were assessed using a life cycle analysis approach based on ISO 14040. After aggregation the environmental data were combined with the corresponding cost data in an eco-efficiency analysis.

Displaying the results in an eco-efficiency portfolio provides a comprehensive mapping of the results.

The eco-efficiency analysis is a tool which is able to structure the link between environment and cost and is able to analyse questions concerning the efficiency of the various recovery measures. As this study was peer reviewed by independent experts the results should facilitate fact-based discussions with the various stakeholders. The study is a first step, based on existing data, completed by expert judgement, involving the inherent limitations of a first approach.

2.3 Analysed parts and use of recyclates

In vehicles, different types of plastic are used in the production of different components. The driving factors for the use of plastics in transportation are light weight (low density of plastics) as well as specific combinations of properties and economic processability. In modern cars, the total share of plastics is estimated in the range of 10-15% by weight with a clear tendency to grow.

In order to evaluate the differences between the recovery options, this study investigated the recovery of seven plastic parts made from different plastic types and representing different sizes and weight (0.27 kg – 3.14 kg, see table 1.1 below), in terms of eco-efficiency.

A key to the generation of high performing recyclates from the various plastic materials used in a car is explicit identification and type specific separation. Without this pre-treatment, the recyclate can only be used for low quality applications with very limited markets. Recyclates generally do not achieve the technical performance of virgin material. To extend their use they are normally blended with virgin material.

Pre–treatment for mechanical recycling generally requires the dismantling of the plastic parts. In contrast to other recovery options, both dismantling and treatment are cost-intensive process steps.

Table 2.1 Analysed plastic parts

Part	Weight (kg/part)	Material	Filler
Bumper	3.14	PP	No
Seat cushions	1.20	PUR	No
Intake manifold	0.72	PA	30% glass fibre
Wash-liquid tank and lid	0.43	PE	No
Air duct	0.95	PP	20% talcum
Headlamp lens	0.30	PC	No
Mirror housing	0.27	ABS	No

2.4 Sensitivity analysis

Eco-efficiency is based on model scenarios and should be interpreted accordingly. In order to get an impression on the consequences of changing parameters, a sensitivity analysis was performed in three different areas:

- **Toxicology**

As risk potential and toxic potential are not included in a standard LCA, two borderline cases were analysed to evaluate their possible impacts on the eco-efficiency portfolio (A: Toxic and risk potentials for all options equivalent; B: No toxic and risk potentials included).

- **Substitution factor (S)**

The environmental benefit of mechanical recycling is strictly related to the substitution factor. The substitution factor is the quantity of virgin material (in kg) that can be substituted by 1 kg of recyclate in the end product in order to achieve **equivalent** performance. For example, if a 500 g plastic part made from virgin material could only be substituted by 1 kg of recyclate, then S = 0.5. (**Warning:** The substitution factor contains no information on the proportion of recyclate in the relevant application).

The study base case assumes an ideal waste stream with S=1. This means that in the case of mechanical recycling, recyclate substitutes virgin plastic material completely (1/1 substitution). This represents a “best-case” scenario.

Knowledge about the potential applications is limited and therefore the results obtained for mechanical recycling cannot be transferred to the total amount of potentially recyclable plastic. The potential market share of recycled plastics is outside the scope and goal of this study and has therefore not been estimated.

Practical experience shows that, due to application requirements, under real market conditions a substitution factor of 1 can hardly ever be achieved in automotive recycling. Therefore substitution factors lower than 1 were analysed in this study.

The best way to increase the quality of recyclates is to blend the recycled plastics with virgin material (e.g. recycled plastic:virgin plastic = 1:4). This means that the volume of marketable recyclate exceeds the volume of plastics used by a very large margin, leading to severe market constraints.

- **Future technologies**

Limited experience shows that plastics from ELVs can be treated in the described technologies. For some routes pilot trials have been performed but these are often too small to provide reliable information on technology performance and real costs, including the investment required for a full industrial-scale plant. In addition to standard processes, one pilot-scale recovery options (Galloo process) is analysed and assessed.

In order to generate the appropriate input data for the eco-efficiency analysis, the individual process steps were investigated and theoretically assembled into a corresponding process chain.

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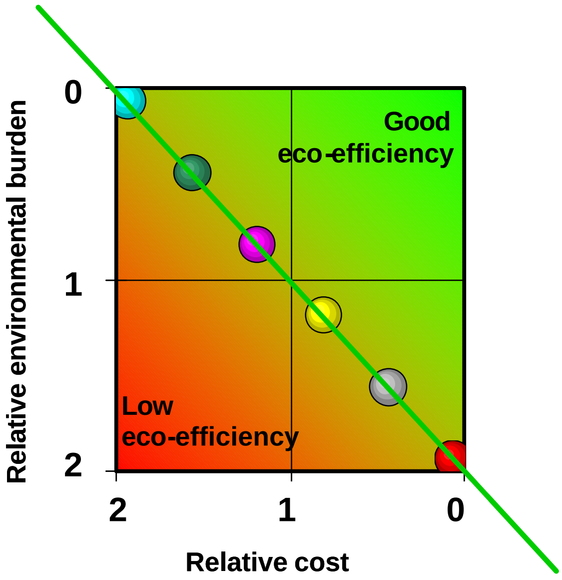
2.5 The eco-efficiency portfolio – a general explanation



An eco-efficiency portfolio displays the relative costs and the environmental impact of different scenarios (=technologies) for a specific plastic part. The eco-efficiency of each recovery option assessed is shown as a bullet. The triangular zone on the right of the chart above the median diagonal represents an area of high eco-efficiency with low environmental impact and cost. Similarly, the lower left triangle, below the median diagonal, represents the area of low eco-efficiency with high environmental impact and cost. All bullets located on a line parallel to the median represent equivalent eco-efficiency. For example, by moving along this diagonal, a higher cost can be compensated by better environmental performance and vice versa.

2.6 General results

- Landfill in most cases shows the worst eco-efficiency performance, despite the fact that a “state-of-the-art” landfill was chosen. The results support the measures to restrict landfill.
- Recovery technologies such as blast furnace, syngas production (SVZ-technology), cement kiln and in some cases to a lesser extend waste combustion generally score at a similar level.
- In terms of eco-efficiency and environmental performance, blast furnace and syngas production perform slightly better than cement kilns and

waste combustion including energy recovery. Generally the differences are small and depend on the specifics of the plants.

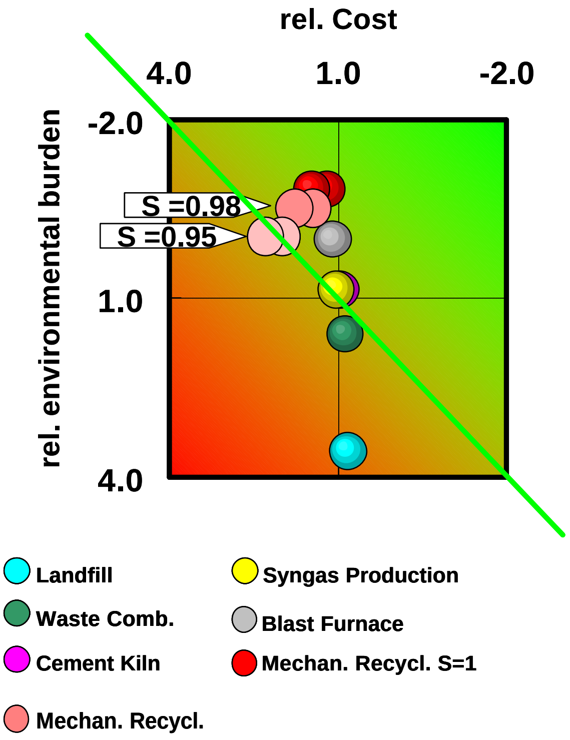
- From an eco-efficiency perspective, mechanical recycling can only compete with other recovery technologies when large, easily accessible monomaterial plastic parts are involved. In this study, this is valid for the bumper and the air intake manifold.
- Dismantling costs are the determining factor for the eco-efficiency performance.
- Assuming a 1 to 1 substitution of virgin by recycled material in an application, the purely environmental perspective shows advantages compared to the other recovery technologies. This base case substitution factor does not take into account the technical feasibility.
- Increased car weight, e.g. due to the reduced performance of recycled materials compared to virgin plastics, is counterproductive. A lower performing recycled material requires additional material weight and consequently fuel consumption during the use phase. In the case of closed loop use in a bumper, a model calculation showed that only 5% additional weight will equalize the environmental performance of mechanical recycling with the best of all other options in terms of eco-efficiency. Alternatively to closed-loop recycling, open-loop recycling may be chosen.
- Energy (weight) savings during the use phase should have highest priority. An analysis assessing the relevance of the recovery phase compared to the whole life cycle (production, use, recovery) of the car clearly indicates that the energy consumption (key indicator) is dominated by the use phase. The “energy” credit from all recovery operations, in comparison, is small (4% for combustion technology; 13.5% for mechanical recycling).

2.7 Results by application

The following paragraphs summarise the eco-efficiency results for the seven analysed parts. Additionally, the portfolios display, where available, the results of significant changes during a sensitivity analysis. In the case of mechanical recycling, the base case portfolios always include both the minimum and maximum dismantling time, so for this recovery option, two eco-efficiency results are displayed.

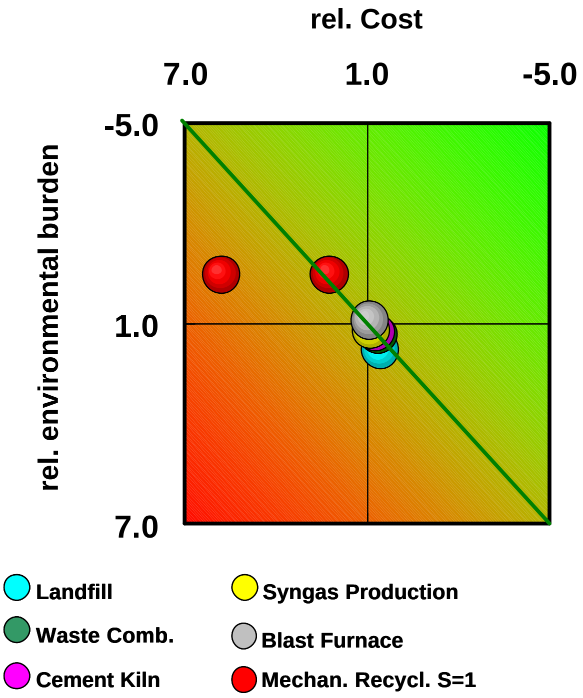
The discussion highlights results not covered in the above chapter, general results.

Bumper Portfolio including substitution factor for closed loop recycling



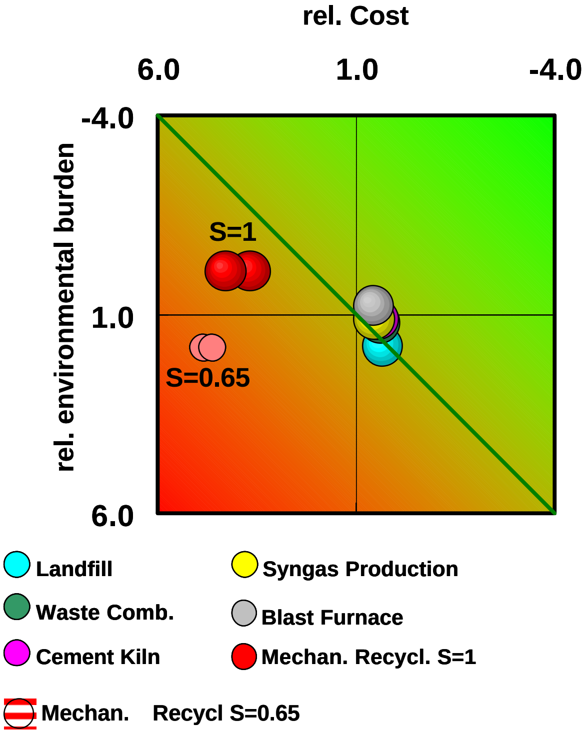
The bumper represents the largest plastic part analysed. The dismantling costs are low as the plastic part is easily accessible. It was assumed that the bumper material does not need to be compounded. Based on this assumption, mechanical recycling in the case of a 1/1 substitution (S=1) is assessed to be the most eco-efficient option for both minimum and maximum dismantling times. The sensitivity analysis, which represents the real market case, involving lower substitution factors in an open loop scenario, leads progressively to an eco-efficiency for mechanical recycling that is equivalent to that for gasification or blast furnace technology. Landfill, as expected, represents the worst option.

Air intake manifold



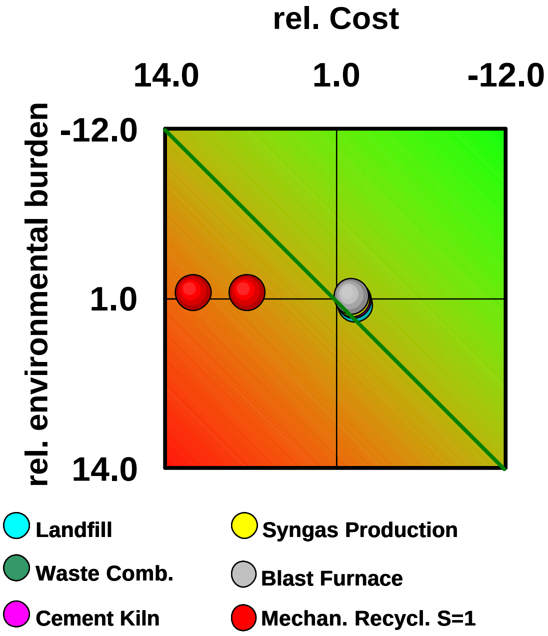
The air intake manifold represents an example where plastics are increasingly replacing metals in the engine compartment. Assuming minimum dismantling costs, the eco-efficiency of mechanical recycling is nearly equivalent to the other best-treatment options (cement kiln, blast furnace and syngas production), but drops significantly when dismantling time is increased. From the environmental perspective alone, mechanical recycling appears to be the best option. The mechanical recycling option shows a very large difference between the minimum and maximum dismantling costs (depending on the location of the part).

Seat cushions including substitution factor for open loop recycling



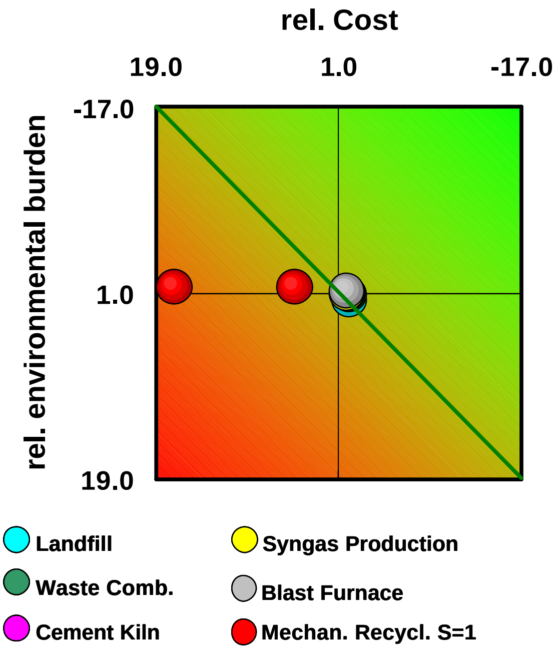
Dismantling and processing determine the high costs for the mechanical recycling of seat cushions. It was assumed that the PUR recyclate replaces virgin material in a non-automotive application such as carpet underlay. Due to the fact that the environmental benefit of mechanical recycling scores low in comparison to costs, this option exhibits the worst eco-efficiency compared with all other treatment options of which cement kiln, blast furnace and syngas production score best. The sensitivity analysis on the substitution factor shows that due to the higher density of the foam made from recyclate material (S<1), this alternative results in higher costs as well as in a worse environmental performance.

Airduct



Air ducts are hidden behind the dashboard. Consequently, the cost of dismantling this relatively small part is very high and is a major determining factor in the analysis. Even assuming ideal substitution conditions (S=1), the overall eco-efficiency of mechanical recycling represents the worst option. No sensitivity analysis for mechanical recycling based on a realistic substitution factor was therefore performed. Because of the scale of the chart, the eco-efficiencies of the other treatment options are located in the same area, with blast furnace ranking highest and landfill lowest.

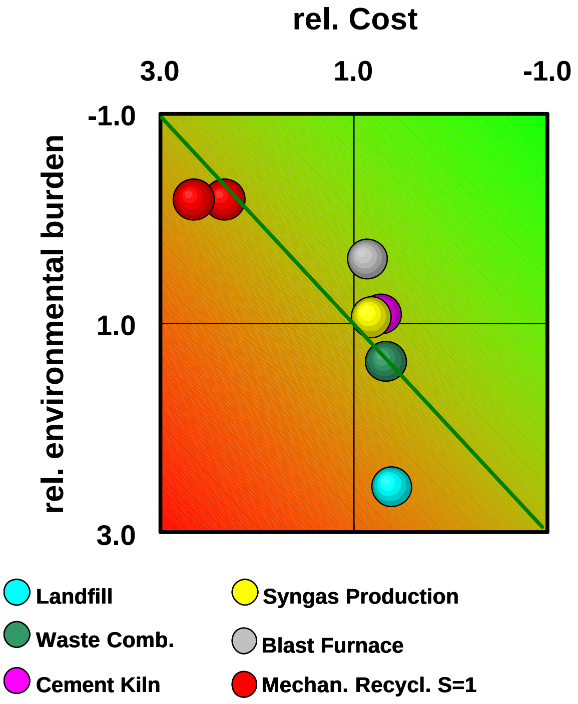
Mirror housing



The mirror housing represents a small part, located on the external surface of the car. The dismantling costs depend on the design of the part. The eco-efficiency score for mechanical recycling of an easily accessible mirror housing is worse than all the other options. Because of the difficulty of dismantling, parts comprising a more complex design exhibit by far the worst eco-efficiency for mechanical recycling.

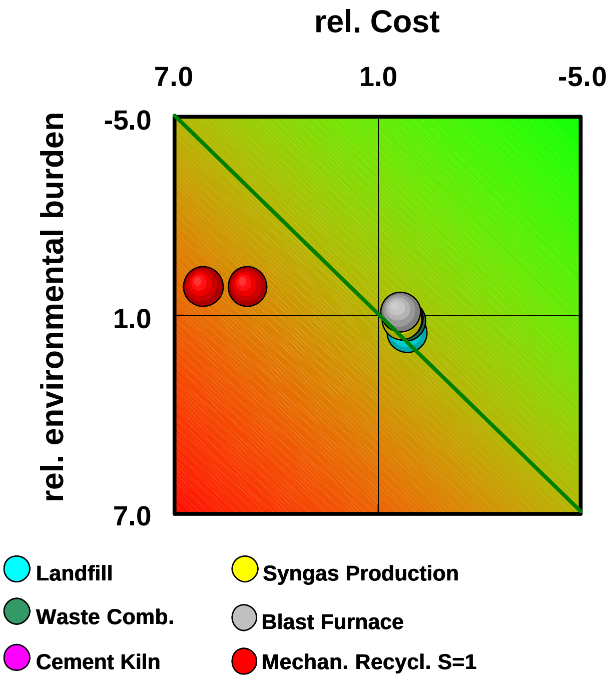
The energy or feedstock recovery options cement kiln, syngas production and blast furnace exhibit the best eco-efficiency.

Wash-liquid tank



The wash-liquid tank, including its lid, represents an easily accessible, medium weight (size) car part. Mechanical recycling shows good environmental performance but higher costs than the other options. From the perspective of eco-efficiency, mechanical recycling with minimum cost is equivalent to waste combustion but worse than the blast furnace, cement kiln or the syngas production.

Headlamp lens



The mechanical recycling of headlamp lenses shows a very poor eco-efficiency due to high dismantling costs. As the lens is part of a complex headlamp structure, dismantling is highly labour intensive. Although the environmental score for mechanical recycling is slightly better than for all the other options, the other options exhibit a better overall eco-efficiency performance.

The best eco-efficiency performance is shown by the blast furnace, cement kiln and syngas production.

3 Introduction

3.1 Preface

APME commissioned a study: “Recovery Options for Plastic Parts from End-of-Life Vehicles: An Eco-Efficiency Assessment” from a consortium of Öko-Institut (project leader) and BASF AG, Germany. This report covers the following working steps:

- Life Cycle Analysis (LCA) of “recovery options” for plastic parts from End-of-Life-Vehicles (ELVs)
- Costs estimates for processes covered in the LCA
- Eco-efficiency analysis: Combination of weighted LCA and cost data in a portfolio for recovery options of plastic parts.

For the waste management of used cars the EU Directive on ELVs sets new legislative standards. Waste sites for ELVs will be better controlled and recycling targets have been introduced on the basis of the total weight of the car. The targets will be extended over time. For steel scrap the recycling route is well established, technically as well as institutionally. Plastics materials from ELVs are part of the shredder waste and are normally landfilled at the present time. The EU Directive will oblige industry to build up new recovery and recycling capacities.

This study is intended to contribute to the ongoing discussion on recovery options for plastic materials, their environmental benefits and corresponding costs. Potential recovery options have been analysed for plastic components of different sizes and material compositions. The results are available as LCA and cost data. Weighted data is shown in a portfolio format (eco-efficiency tool).

3.2 Overview

Plastics are widely used in automobiles today. During recent decades the introduction of new light materials has had a double impact:

1. Light materials enable the automobile industry to save weight and thus, in theory, build energy-efficient automobiles.
2. The change from traditional steel to other materials reduces the amount of valuable, easy to separate materials in the vehicle at end of life. From a recycler’s point of view, recovery of material from modern automobiles is not financed by the value of the material recovered.

The European Union has established an “End-of-Life-Vehicle” (ELV) Directive, in which targets for recycling/recovery have been set based on the total weight. Starting in 2005, reuse and recovery should be increased to 85%, reuse and recycling to 80%. In

2015 the corresponding targets are set at 95% for reuse and recovery and 85% for reuse and recycling. Depending on the material composition of ELVs, recycling / recovery of plastics may be necessary to fulfil the targets. This study uses the eco-efficiency approach to assess the recycling/recovery options for selected plastic parts.

The study is divided in the following steps:

1. LCA data set for plastic parts for different recycling/recovery options
2. Cost data set for the above described LCA data sets.
3. Eco-efficiency assessment for the described LCA/cost data sets.

The selection of the parts to be studied was made based on expert judgement.

This focus of the LCA was on the recycling/recovery options. LCA´s on the life cycle of plastic parts in automobiles were performed on selected parts in order to show the relevance of the recycling/recovery activity.

Cost data was developed in parallel to the LCA.

The basis of the study was LCA and cost data. For each plastic part this data base has been combined in a portfolio-type analysis, the eco-efficiency analysis. The eco-efficiency analysis displays a weighted environmental benefit versus cost and helps to assess the efficiency of different measures/options. These highly aggregated results have to be analysed carefully using a step-by-step analysis of single results.

3.3 Selection of plastic parts

Automobiles contain some 100 plastic parts of different size and materials. The amount of plastics content in vehicles varies from model to model. It depends on age, total weight, style and manufacturer. A detailed list of all the plastic parts in a specific car is not available. It is estimated that large, medium and small sized parts contribute in a similar way to the total amount. The parts in this study have been selected by expert judgement, supported by a transparent selection process.

From the selection process 7 parts were identified: 3 large, 3 medium and 1 small.

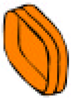
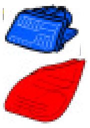
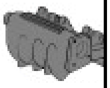
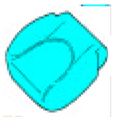
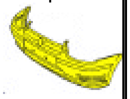
Size	small	medium			big		
Part	Mirror housing (finisher) 	Lamp 	Air system 	Wash fluid tank+lid  (lid)	Intake manifold 	Seat cushion 	Bumper 
Plastics	ABS Group (incl. total mirror)	PC Group (incl. total lamp)	PP Group (incl. dashboard)	PE Single part	PA Single part	PUR Single part	PP

Figure 3.1 Selected plastic parts.

4 Sponsors, Realisation and ISO Conformity

4.1 Sponsor

The sponsor of this study is the Association of Plastics Manufacturers in Europe (APME) Brussels. Contact is Herbert Fisch.

4.2 Realisation

The study was conducted by Öko-Institut in cooperation with BASF. Contact is Wolfgang Jenseit, Öko-Institut.

4.3 ISO Conformity

The study consisted of 3 parts:

1. Life Cycle Assessment (LCA)
2. Costs analysis
3. Eco-efficiency analysis (Aggregation of costs and environmental impact.)

Part 1. (life cycle assessment) was conducted according to ISO 14040, version 1997[2]. For part 2 (cost analysis) and part 3 (eco-efficiency analysis) no corresponding standards exist as yet: they were conducted according to the principles of scientific work.

4.4 Methodological framework

For about ten years, life cycle assessments (LCAs) have been carried out in large numbers. These have included both very detailed and streamlined/simplified LCA studies. The methodology used has been developed in parallel with this expansion in use. In the scientific community and in the environmental policy domain, intensive efforts have been made towards the establishment of methodological conventions and continue to be under way. At the international level, the Society of Environmental Toxicology and Chemistry (SETAC) published an influential framework paper in 1993 ("Guidelines for Life-Cycle Assessment: A Code of Practice"). This work has been continued through the extensive activities of national and international standards organisations (DIN, EN-ISO). ISO 14040, "Environmental Management – Life Cycle Assessment – Principles and Framework" was finalised in July 1997. This standard sets out the principles and framework for performing LCA studies, and minimum requirements (e.g. for LCA reporting). Detailed requirements for the individual LCA phases are: a standard on the goal and scope definition of a life cycle inventory analysis

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[2] International Standards Organisation 1997. International Standard ISO/DIS 14040:Environmental Management - Life Cycle Assessment - Principles and Framework

(ISO 14041) and standards on life cycle impact assessment (ISO 14042) and life cycle interpretation (ISO 14043).

ISO 14040 -14043 distinguishes between four phases of LCA studies. Table 1 gives an overview, listing the respective elements.

Table 1 – Elements of the ISO standards on LCA studies

Phase	**Brief description**
Goal and scope definition	– Statement of intended application, of the reasons for carrying out the study and the intended audience – Definition and specification of the product systems being studied (e.g. functional unit) and of the scope of the study (system boundaries, allocation procedures, impact categories) – Specification of the requirements upon the inventoried data – Critical review considerations
Life cycle inventory analysis (LCI)	– Data collection and calculation procedures for quantification of the material and energy input and output flows of the product systems studied – Specification of data collection and calculation procedures
Life cycle impact assessment (LCIA)	Mandatory elements: Selection of impact categories, category indicators and models Classification (assignment of LCI results) Characterisation (calculation of category indicator results) Optional elements: Normalisation of category indicator results relative to reference values Grouping Weighting Data quality analysis (*mandatory in comparative assertions)
Life cycle interpretation	– Identification of significant issues – Evaluation by completeness check, sensitivity check, consistency check – Conclusions – Recommendations – Reporting

The study reported here was carried out as a LCA in accordance with ISO 14040. In view of the goal of the study, a review by interested parties was chosen as the critical review procedure (ISO 14040, 7.3.3).

5 Life Cycle Assessment (LCA)

5.1 Goal and Scope of the study

5.1.1 Background

The objective of the study is to calculate the economic and ecological aspects of plastics recycling in end-of-life vehicles. Plastics parts in automotive applications offer technical, economical and environmental advantages. Mechanical recycling of these parts from end-of-life vehicles is comparatively costly due to the manual labour needed for dismantling. The environmental assessment of plastic recycling depends on various conditions like recyclability. Another option is the shredding process for the whole car followed by energy recovery or feedstock recycling of the plastics in the shredder residue. Today, the non-metallic fraction from the shredding process is mainly sent to landfills.

The whole car shredding process (after depollution and the removal of components destined for reuse) followed by recycling of metals and landfilling of the residues has become established as a standard ELV treatment. The EU ELV Directive has put legal obligations concerning recovery and recycling on the car manufacturing industry and the car recycling industry. For plastics materials, a reasonable basis is necessary for the decisions on which parts and materials should be recovered, by which technology and to what extent. Balancing the costs and environmental impacts of the options may help to avoid inefficiencies and adverse effects.

5.1.2 Goal definition

The LCA on recovery and recycling options of plastic parts in ELVs is part of a broader assessment. For the environmental part the LCA methodology is used as a standard framework. The LCA database created as part of this work serves as an input to an assessment scheme and is subsequently integrated into an eco-efficiency portfolio analysis.

Although the recovery and recycling targets in the ELV Directive are fixed, how they can be achieved in practice is still under discussion. This study is intended to provide transparent and reliable data, obtained using a common methodology.

In the case of mechanical recycling, the study focuses on high-quality recycling. This approach is very optimistic[3] and can serve as a benchmark for recycling strategies. It assumes that recycled material will not have a high share of the market for automotive plastics. Instead, a slow introduction and occupation of niches are the underlying assumptions.

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[3] The approach may lead to optimistic figure for the environmental part but although to high dismantling costs.

The LCA carried out here pursues the following two goals:

- Environmental assessment **of different recycling/recovery options of plastic parts in ELVs**.
- Analysis within the recovery or recycling options for plastic parts in ELVs for **benchmarking** different end-of-life treatments and internal learning. The study does not focus on specific improvements

Finally, any further need for research and development should be identified.

As the recovery and recycling of plastic parts from ELVs, a major focus of this study, is not realised yet, the study also covers future developments. Tracking the possible future material flow of plastic parts from ELVs, improving the research on data on these pathways and detecting data gaps are the inherent goals of this study.

5.1.3 Intended audience, critical review and limitations

5.1.3.1 Intended audience

The results of the study are expected to be of relevance both to APME members and to organisations and individuals who are active in the field of treatment of end-of-life vehicles. These will include the relevant sections of trade and industry, car manufacturers, dismantlers, shredders, the recycling and recovery industry and decision makers in politics and administration.

The present report is not intended to be published but it will be publicly available on request.

5.1.3.2 Critical review

A **critical review by interested parties** was chosen for this study. Helen Teulon (former PWC-Ecobilan, Paris) was selected as external expert to act as chairperson of the review panel. In consultation with APME, two further members of the Critical Review Panel were selected by the chairperson. They are: Roland Hischier (EMPA St. Gallen) and Roberto Zoboli (IDSE-CNR).

5.1.3.3 Reports and Compliance

In accordance with the requirements of the sponsor, the report contains three parts:

1. Life Cycle Assessment (LCA) that covers the items required by ISO 14040.
2. Costs analysis
3. Eco-efficiency analysis, being an aggregation of costs and environmental impact.

In the eco-efficiency analysis, a weighting method is used to combine the different environmental burdens into a single note. The authors like to inform the reader, that

1. ISO 14042 does not specify any specific methodology or support the underlying value-choices used to group the impact categories, and
2. The value-choices and judgement within the grouping procedures are the sole responsibility of the commissioner.

5.1.3.4 Limitations on the use of the results of the study

Individual sections of the study can be used, but the purpose and scope of the full report should always be cited.

The field of car recycling is highly innovative and will change in the future. It is also foreseeable that today’s practices for the treatment of the end-of-life vehicles will be improved to fulfil future requirements. This study tries to forecast future developments on the basis of today’s knowledge.

The recovery options were selected on the basis that they are feasible in principle. The capacities for recovery of plastic parts in the future have not been determined. It is not possible to draw any conclusion about a future potential mix of recovery operations on the Western European scale. Further on, the plastic stream from ELV will join other waste streams flow, which generate uncertainties on the relative competitiveness of different treatment options.

The scope is in principle Western Europe, but for practical reasons, most data are representative for the situation in Northern Europe. APME data records for the production of virgin material are mainly based on production sites in UK, the Netherlands and Germany. Estimates for the recovery option “Syngas production” are based on experience with the only existing plant (SVZ) in Germany. For the other options the technology is very similar throughout Western Europe and no significant differences in energy and material flows as well as airborne emissions from the processes are assumed. Environmental impacts on the water pathway (water abstraction, water emissions) are strongly linked to local situations and have to be assessed with great care.

The data on mechanical recycling do not on the whole reflect existing processes; they are expert estimates. The limitations do not result from the data of unit operations but from the overall structure. Therefore the data has to be seen as scenario (if…) data.

5.1.4 Functional unit and representativeness

5.1.4.1 Functional unit

The functional unit of the system is defined as:

> Treatment of one ***discrete*** plastic component in end-of-life vehicles.

Different recycling or recovery options lead to different outputs like recycled material, energy, feedstock or a combination of them. Common to all systems compared is the treatment of 1 plastic component from an end-of-life vehicle.

The study covers 7 selected discrete plastic components in ELVs:

1. Bumper
2. Seat cushions
3. Intake manifold
4. Wash-liquid tank and lid
5. Air ducting system
6. Headlamp lens
7. Mirror housing

5.1.4.2 Geographical and time representativeness

5.1.4.3 Geographical representativeness

The LCA study addresses the EU ELV Directive and is sponsored by a European industry association and is therefore designed to cover Western Europe (EU-15, Switzerland, Norway). Wherever possible, LCA data are calculated for Western Europe. The origins of the data sources will be discussed in the next section. Information research has been organized by APME and covers Western Europe as far as possible.

The study does not reflect different regional strategies or regional differences for processes. LCA data are used for all steps only at an aggregated European level (plastic-APME, Western Europe-electricity grid). Differences in transport emissions between states have not been taken into account, as the trucks are the same. Differences may originate from national transport mix or logistics. For Municipal Waste Combustion (MSWC) and landfill, harmonized LCA data has been developed according to the EU legislation.

5.1.4.4 Time representativeness

The study has a prospective character and covers future processes (target 2005-2010 for ELV treatment), which do not exist at the present time. In principle, the recovery processes are known and practised on a small scale or in well-known unit operations. They need to be adapted to specific process conditions. In theory, an LCA data set of future processes for the years 2005-2010 needs to be developed. This has not been done. For important processes like electricity production or plastic manufacturing, the changes are estimated to be small. Air pollution from transport may change significantly but the overall influence of this category is small. Important changes will be observed in the disposal sector. The LCA data has been selected using the following approach:

1. Common LCA data should reflect processes utilized in the years 1995 to 2000.
2. For selected processes, which have a high impact on single options,[4] foreseeable changes are included. This will be performed for the core processes (shredding, dismantling) and for waste processes which are subject to EU legislation (MSWC, landfill). For the latter processes, data or data sets from existing plants have been taken which (nearly) fulfil the requested requirements.

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[4] As opposed to processes which are used to the same extent in all options and thus, although there may be deviations in absolute figures the effect on relative figures is small.

5.2 Scope

5.2.1 Plastic parts

Plastic parts in automobiles are not uniform in size or material used. Statistics or databases on plastic parts are not public and not available for this project. Thus information on "average, typical" parts has been obtained by means of reviews with experts. The parts that were selected had to be defined according to available information. It is thought that the parts represent standard elements. A mix of elements has not been taken into account.

The next table shows the plastic parts with information on weight, material and surface treatment. Any interaction with other parts has not been taken into consideration.

Table 5.1 Characteristics of the plastic parts

Part	Weight kg/part	Material	Filler	Surface treatment
Bumper	3,14	PP	None	No[5]
Seat cushion	1,2	PUR	None	No
Intake manifold	0,717	PA	30% glass fibre	No
Wash-liquid tank and lid	0,433	PE	None	No
Air ducting system	0,952	PP	20% talc	No
Headlamp lens	0,3	PC	None	Yes
Mirror housing	0,269	ABS	None	Yes

The determination of the weight of the plastic parts would have an impact on the costs if costs per part are taken into account as for dismantling. However, costs, as for gate fees or revenues, are based on weight, so they are not impacted by the chosen weight per part. Unlike cost analysis, the mass and energy flow is characterised by mass-related coefficients (unit per kg or MJ). So the chosen weight of the plastic part does not influence the overall mass or energy balance.

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[5] In this study only unpainted bumpers have been considered. In the future bumpers from ELVs will be (partly) painted.

5.2.2 System boundaries

The next figure gives an overview on the principle pathways for the treatment of plastic parts in ELVs. The process steps involved are:

1. Pre-treatment of the ELV (*depollution and removal*): removal of tyres, batteries, oil, gasoline, lubricants etc. This process step is mandatory for all ELVs according to the EU Directive. The plastic parts considered in this study are not involved in the pre-treatment step. Thus, the pre-treatment process does not contribute to the environmental effects of plastic parts and is not included as part of this LCA (see system boundaries).
2. The next step may be *dismantling*. Whether dismantling of large plastic or other parts become obligatory will be ruled by future national legislation[6]. In this study it was assumed that the parts have to be dismantled for the *mechanical recycling* recovery option.
3. The remainder of the ELV is shredded and separated (*shredding and sorting*) into iron scrap, shredder fraction (nonferrous metals) and shredder light fraction (fluff, the only fraction remaining inside the system boundary) which contains plastics and materials of similar weight.
4. For the transport of the plastic after shredding a transport distance of 35 km (landfill) and 50 km (incineration) is estimated. For cement kiln, blast furnace and gasification the transportation distance is 600 km. Available capacity in Europe and their location are not taken into account in this study.

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[6] In the German ELV directive, the dismantling of large plastic parts (bumper) is foreseen.

The plastic material in fluff may then be treated in different processes (landfill, MSWC, cement kiln, etc.). For some of these, additional pre-conditioning (e.g. mechanical treatment of fluff) may be necessary. Most of the processes produce materials (i.e. raw materials) or energy which replace the primary production processes of material or energy.

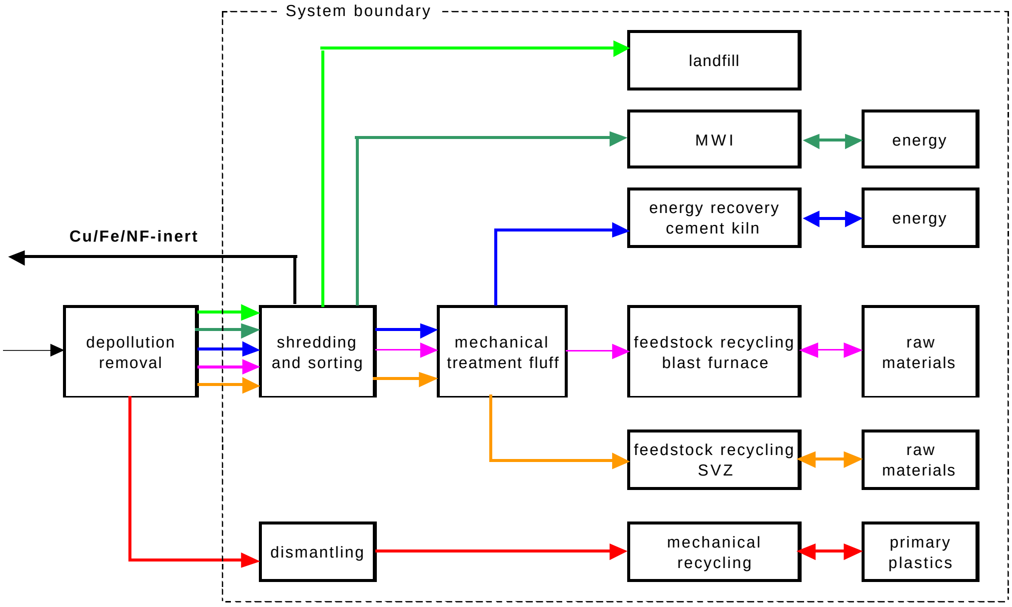

Figure 5.1 Recovery options for end-of-life vehicles

Within the above scheme an LCA can be developed in one of two ways:

1. Gross balancing: Tracking the flow of one discrete plastic part through the treatment scheme for the different options, ***including*** all materials of an ELV (iron, non-iron, plastic and others) for the treatment of one total ELV in a base case or
2. Net balancing: Tracking the flow of one discrete plastic part through the treatment scheme, ***excluding*** all other materials of an ELV.

For this study, the net balancing approach was chosen. In the following description, the flow within the system boundary refers to the discrete plastic part only.

The following recovery/recycling options are covered:

1. Landfill
2. Municipal Waste Combustion (MSWC)
3. Cement kiln
4. Syngas production
5. Blast furnace
6. Mechanical recycling

5.2.2.1 Landfill

The process steps included are:

- Shredder: Only the shredding and separation of the plastic part is considered in the whole process of shredding of the end-of-life vehicle and separation of the fraction fluff. The plastic part considered is part of the fraction with high heat value (plastic in fluff, inside the system boundary), whereas non-ferrous metals (including inert materials) and ferrous metals (both fractions are shown in italics) are not part of the system under examination (outside the system boundary)
- Landfill: Disposal of the fraction with high heat value (plastic in fluff)
- Waste water treatment: treatment of seepage water from the landfill
- Transport: i.e. transport from a shredding plant to a landfill.

The general methodology and process steps for the calculation of the landfill recovery option are given in the figure below.

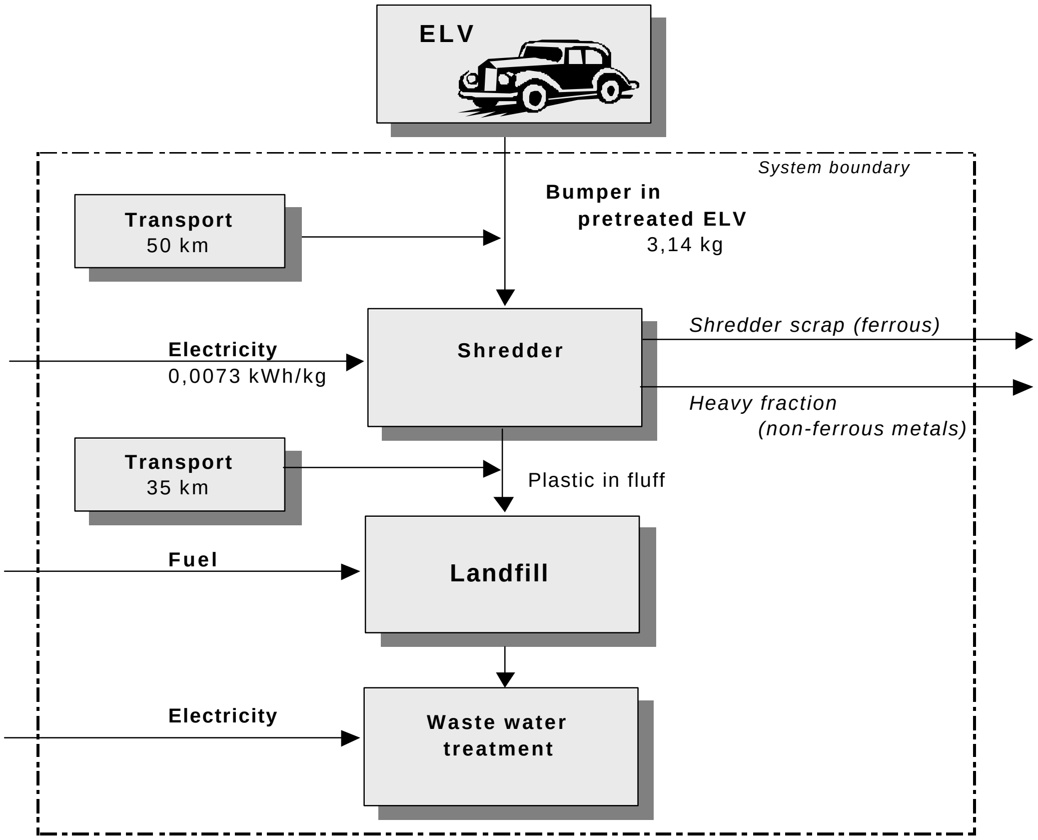

Figure 5.2 Landfill: example of the plastic part "bumper".

5.2.2.2 Municipal Waste Combustion (MSWC)

The option "MSWC" covers the following steps:

- Shredder: Shredding of the end-of-life vehicle and separation of the shredder residue light fraction (fluff); the plastic part considered is part of the fraction with high heat value (plastic in fluff, inside the system boundary), whereas non-ferrous metals/inert materials and ferrous metals (both fractions are shown in italics) are not part of the system under examination (outside the system boundary)
- Municipal Waste Incinerator: Co-combustion of the plastics fraction together with municipal waste in a MSWC an average plant which produces steam and electricity is considered
- Treatment of ashes: The ashes are further treated for use as a construction material in road building; the flue gas residues are landfilled without further treatment.
- Benefit: Bonus for the replacement of the generation of electricity and heat
- Transport: i.e. transport from a shredding plant to a MSWC.

The general methodology for the calculation of the municipal waste combustion recovery option is shown in the figure below.

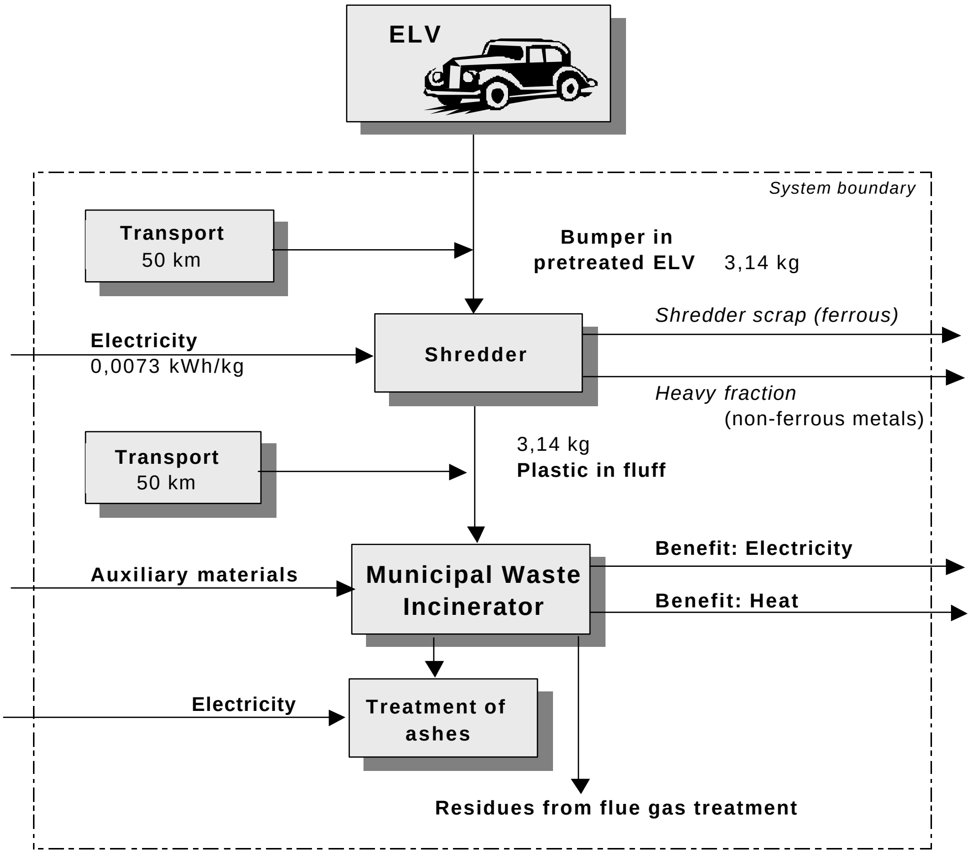

Figure 5.3 Municipal Waste Combustion (MSWC): example of the plastic part "bumper".

Calculation Method

The calculation of the emissions from waste combustion is based on emission limits taken from the EU Directive for waste combustion. Emission factors are derived from these emission limits. Emissions are calculated by using the emission factors and the input-related amount of flue gas. The applied calculation model is described in the Annex.

The generation of energy as a "product" from the combustion process is based on the energy input of the fluff. A recovery rate of 40% of the energy in the fluff is assumed. The energy is used at the European average (12% electricity, 28% heat).

The amounts for the auxiliary materials and the residues from flue gas treatment are average data from literature [DSD 2001].

The amount of ashes resulting from the combustion process is calculated from the inert input material and from the amount of material (burnable), which remains unburned during the combustion process. The ashes are further treated (the treatment facility requires electricity) and used as a construction material in road building. The material is subject to elution. The resulting emissions are input dependent (harmful substances in fluff). The emission calculation is based on the input (fluff), the amount of precipitation and the elution rate.

5.2.2.3 Cement Kiln

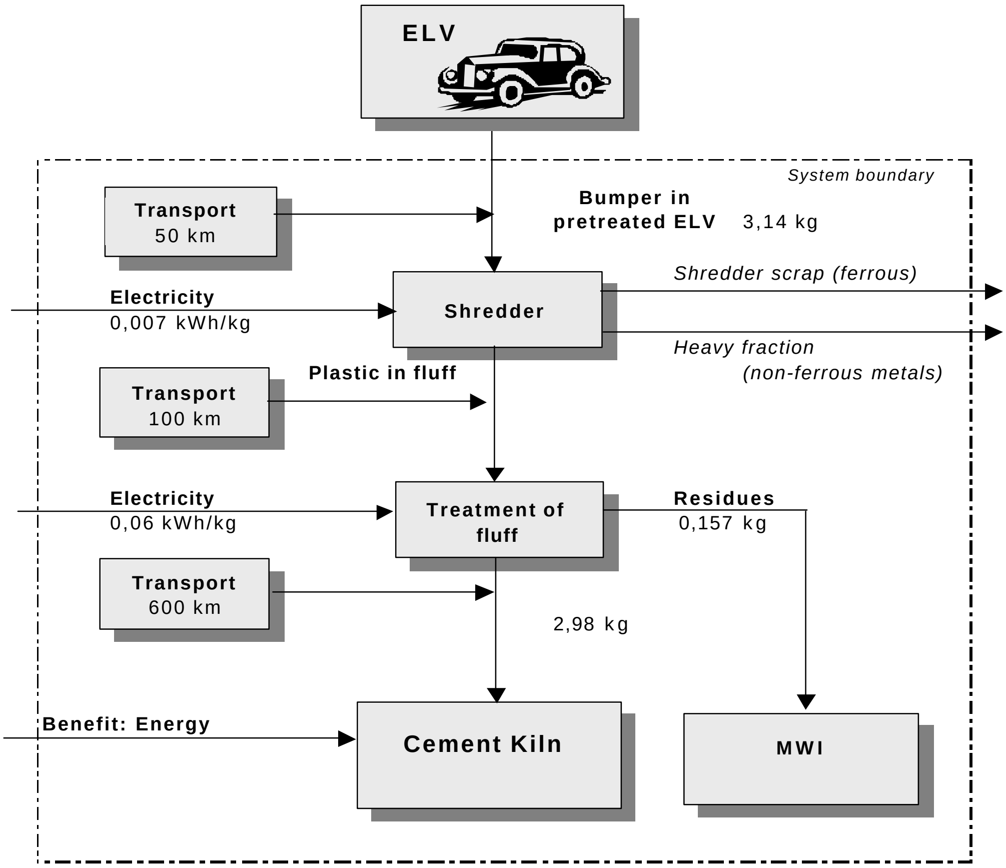

Figure 5.4 Cement kiln: example of the plastic part "bumper".

The recovery option "Cement kiln" covers the steps:

- Shredder: Shredding of the end-of-life vehicle and separation of the shredder residue light fraction (fluff); the plastic part considered is part of the fraction with high heat value (plastic in fluff, inside the system boundary), whereas non-ferrous metals/inert materials and ferrous metals (both fractions are shown in italics) are not part of the system under examination (outside the system boundary)
- Treatment of fluff: Further separation process of the fraction with high heat value
- Cement kiln: Input is the processed fraction with high heat value (plastics)
- Benefit: Bonus for the replacement of the generation of process heat from coal and lignite
- Transport: i.e. transport from a shredding plant to a cement kiln

- MSWC: Treatment of residues, waste combustion is generally chosen as the treatment for residues occurring within all recovery options.

The general methodology and process steps for the calculation of the cement kiln recovery option are shown in the figure above.

5.2.2.4 Syngas Production

The recovery option “Syngas production” includes the following steps:

- Shredder: Shredding of the end-of-life vehicle and separation of the shredder residue light fraction (fluff); the plastic part considered is part of the fraction with high heat value (plastic in fluff, inside the system boundary), whereas non-ferrous metals/inert materials and ferrous metals (both fractions are given in italics) are not part of the system under examination (outside the system boundary)
- Treatment of fluff: Further separation process of the fraction with high heat value
- Compacting: Compacting of the processed fraction with high heat value in order to achieve the input specification of the gasification process
- Syngas production: The gasification process; input is the processed fraction with high heat value (plastics)
- Benefit: Bonus for the replacement of the production of methanol, nitrogen and electricity
- Transport: i.e. transport from a shredding plant to the syngas production
- MSWC: Treatment of residues, waste combustion is generally chosen as the treatment for residues occurring within all recovery options.

The main process steps for the calculation of the recovery option landfill are shown in the following figure.

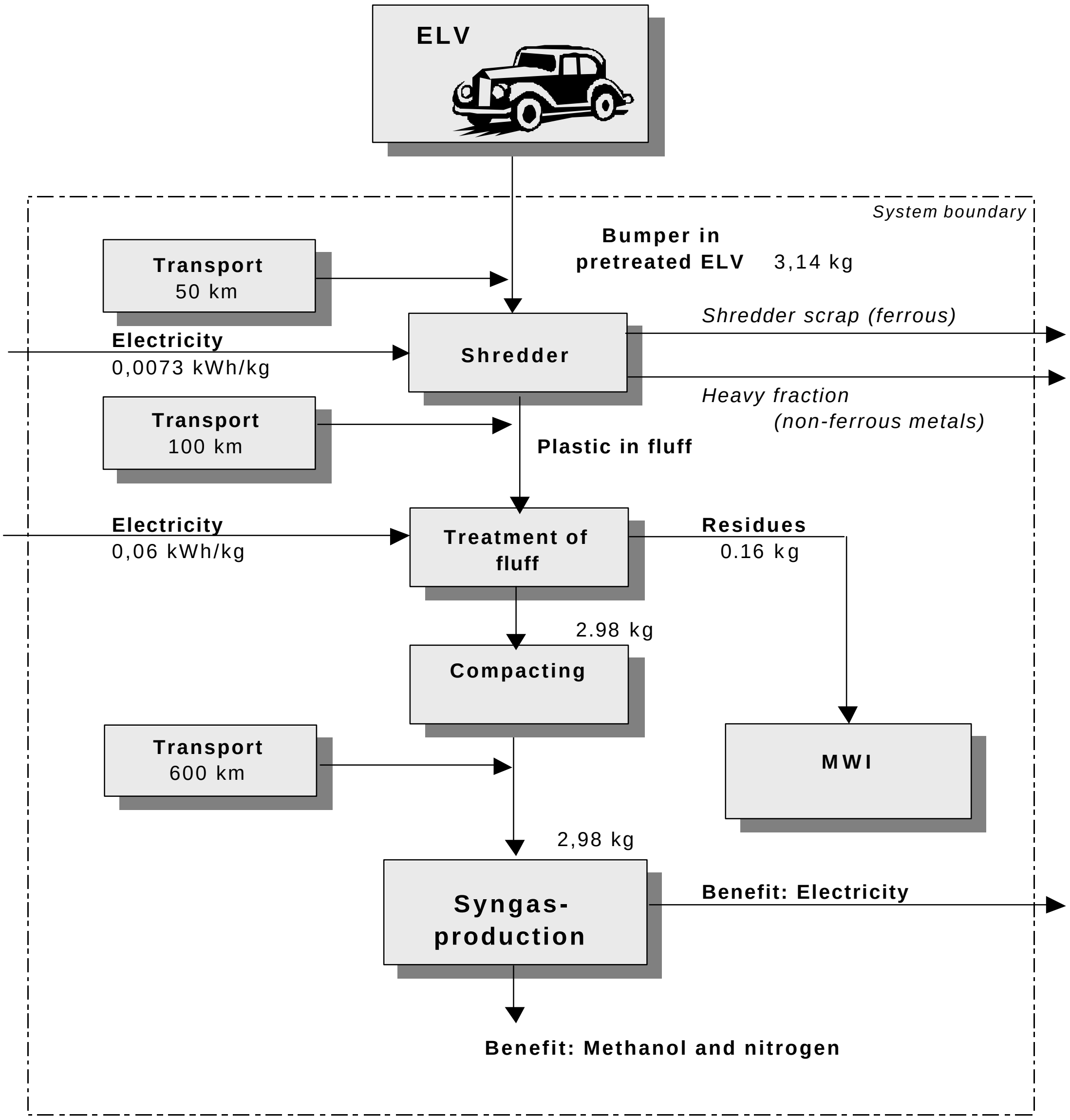

Figure 5.5 Syngas-production: example of the plastic part “bumpers”.

5.2.2.5 Blast Furnace

In a blast furnace, material of high calorific value may be used to substitute heavy fuel oil or coal. Plastics also function as a reducing agent blown in the bottom of the blast furnace. The system boundary includes the following steps:

- Shredder: Shredding of the end-of-life vehicle and separation of the shredder residue light fraction (fluff); the plastic part considered is part of the fraction with high heat value (plastic in fluff, inside the system boundary), whereas non-ferrous metals/inert materials and ferrous metals (both fractions are shown in italics) are not part of the system under examination (outside the system boundary)

- Treatment of fluff: Further separation process of the fraction with high heat value
- Agglomeration: Agglomeration of the processed fraction with high heat value in order to achieve the input specification of the blast furnace
- Blast furnace[7]: Reduction process in steelworks; input is the processed fraction with high heat value (plastics)
- Benefit: Bonus for the replacement of heavy oil and difference in emissions resulting from substitution in blast furnace.
- Transport: i.e. transport from the shredding plant to the steelworks
- MSWC: Treatment of residues from various process steps, waste combustion is generally chosen as treatment for residues occurring within all recovery options.

The main process steps of the recovery option blast furnace are given in the following figure.

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[7] For a detailed description see Annex, part I.

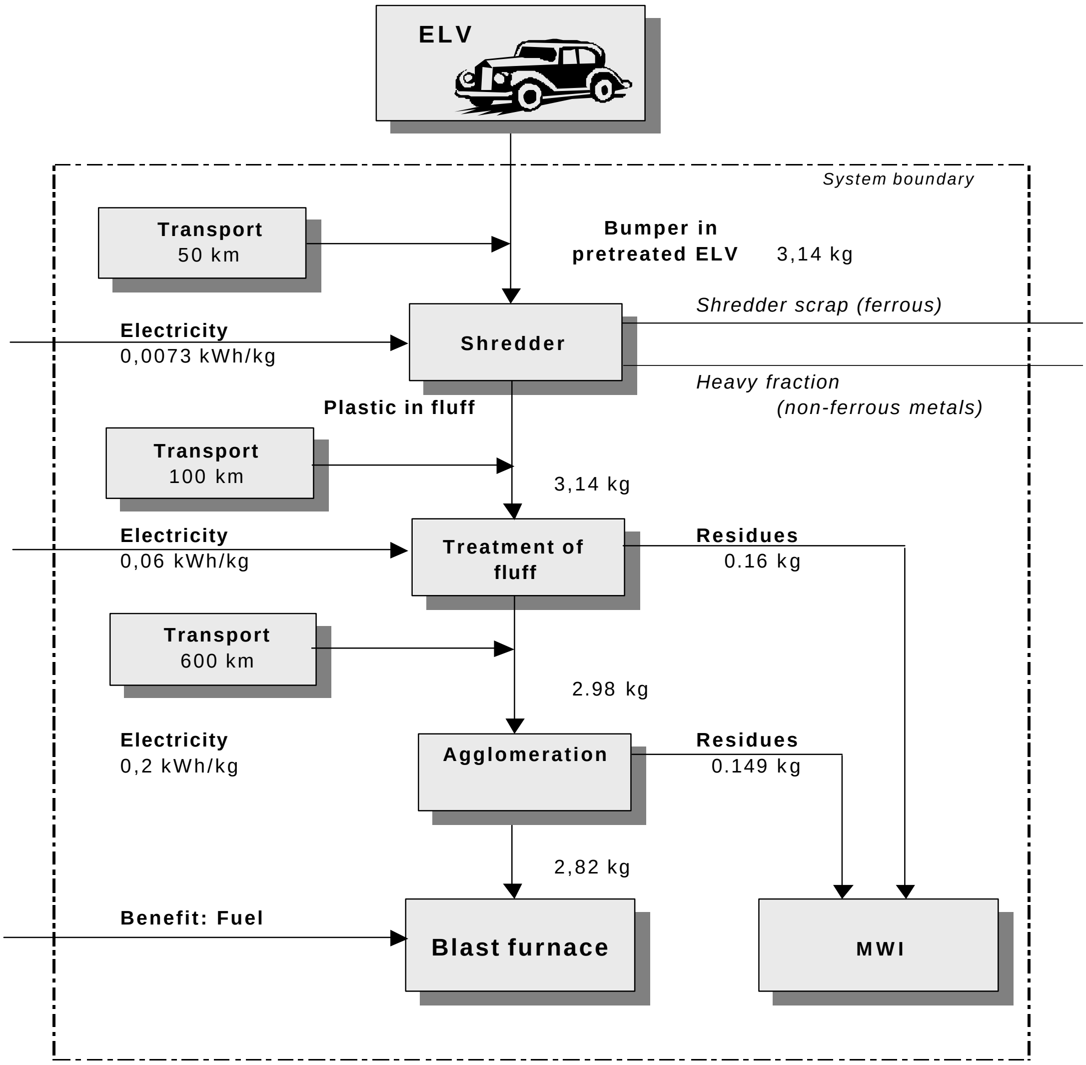

Figure 5.6 Blast furnace: example of the plastic part "bumper".

5.2.2.6 Mechanical Recycling

The main process steps are

- Dismantling: Removal of individual plastic parts (takes place within the same process step as the removal of the battery, the engine or the tyres)
- Processing: Shredding, grinding and sorting of the dismantled plastic part
- Paint removal: Only relevant for painted or surface coated plastic parts (headlamp lens, mirror housing)
- Compounding: Final process step for the production of secondary granules

- Benefit: Recycled granules; for the replacement of primary plastic granules, a credit for the equal-weight production (substitution factor) of virgin material is given.
- Transport: i.e. transport of plastic parts from the place of dismantling to the place of mechanical recycling
- MSWC: Treatment of residues from various process steps; waste combustion is generally chosen as the treatment for residues produced by all recovery options. The calculation is based on the MSWC which is described in the recovery option MSWC.

The general methodology is shown in the figure below.

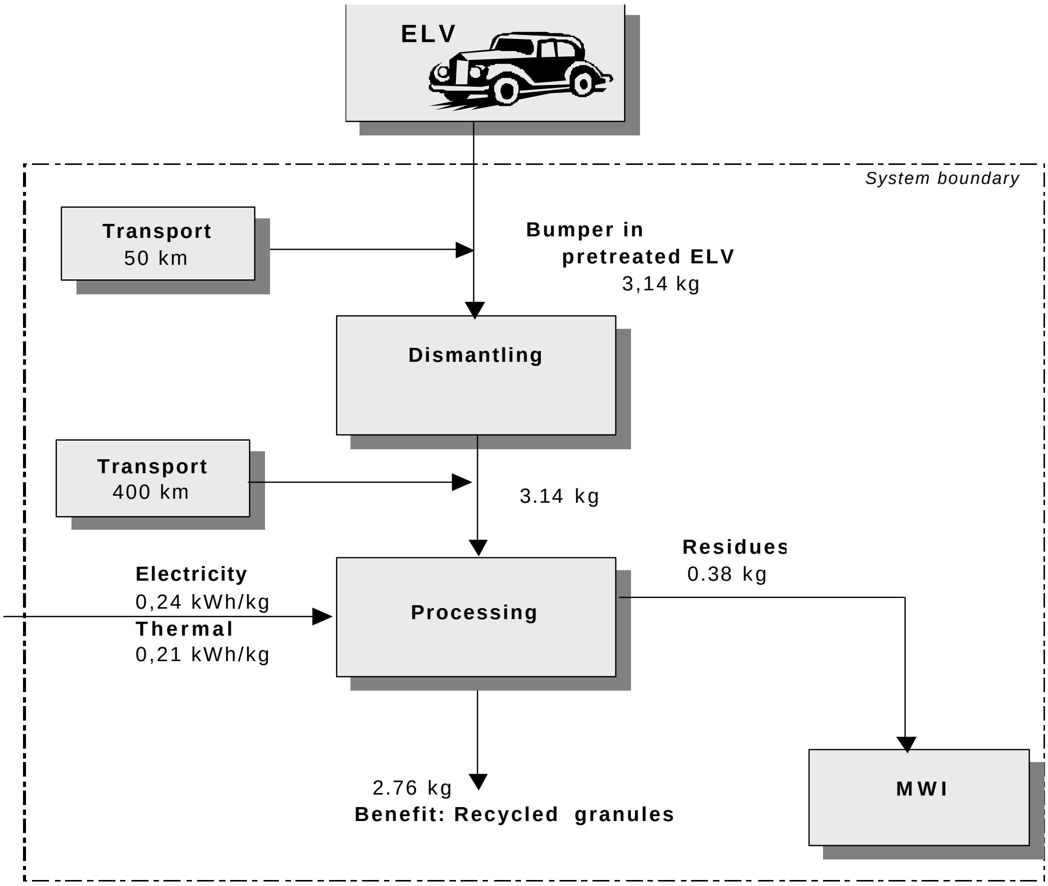

Figure 5.7 Mechanical recycling: example of the plastic part "bumper".

Balancing principle

For mechanical recycling of post-consumer plastic, the substitution factor is a key element:

$$\frac{\textbf{Virgin plastic in product A}}{\textbf{\textit{Recycled plastic in product}}} = \textbf{\textit{Substitution factor}}$$

Three main balancing principles in life cycle analysis have been identified for the substitution factor and well-known examples have been described in the literature:

1. **“Substitution of virgin material with a substitution factor near 1”:**
   If the recycled plastic is able to substitute the same amount of virgin material in plastic products without loss in performance, the recycled plastic is accepted as a full substitute and the amount of recycled plastic may get the bonus for non-production of virgin material.
2. **“Substitution of virgin material with a substitution factor less than 1”:**
   Recycling of post-consumer plastic generates recycled material which has suffered a significant decline in its physical/chemical properties. For some products this recycled material can be used if the loss in specific properties is compensated with higher weight (e.g. thicker films, thicker parts). The ratio of substituted virgin material to recycled material is given by the substitution factor. The recycled plastic is accepted as a substitute and gets the bonus for non-production of virgin material, but only to the extent to which virgin material is substituted.
3. **“Substitution of other materials (downcycling)”**
   If substitution of virgin material in products is not possible, the recycled material can still substitute other material such as wood or concrete. Typical applications are wooden seats or noise protection barriers. The recycled plastic is therefore accepted as a substitute for these materials and gets the bonus for non-production of these materials, but only to the extent to which these materials are substituted.

In the base szenario of this study a substitution factor of 1, was taken into consideration. The reasons are:

1. Plastics in automobiles have to fulfil high specification criteria. As virginb material they therefore have uniform properties and are optimised for the specific applications.
2. Recycled plastics could only replace virgin plastic if they could meet the specifications.
3. With respect to market demand, the applications for plastics with a substitution factor lower than 1 are very limited.

4. In this study, it was chosen to dismantle plastic parts from ELVs before treatment. This theoretically leads to good seperation and should lead to a homogeneous fraction. A more elaborate detection system could be applied as these are under development for other post-consumer plastics.
5. The recycling of ELV plastic mainly has been demonstrated in studies on laboratory ot pilot scale yet.

This assumption is in accordance with the goals in this study. The focus is on high-quality recycling, which is slowly introduced by occupation of niches. Nevertheless this assumption must be regarded as a “best case” scenario.

The further impact of the substitution factor is discussed in Section 8.

In practice, the mechanical recycling of ELV plastics after dismantling includes the following steps:

1. Shredding and grinding
2. Blending with virgin materials to enhance physical strength
3. Compounding.

The initial process steps (shredding and grinding) cause losses in physical strength, which is compensated by adding virgin material. Typically, the virgin material could make up to 60% of the compounded product.

The blending ratio limits the extent to which recycling plastic can enter the market for automotive plastics.

5.2.3 Data sources and data quality

5.2.3.1 General

The data sources can be classified in two groups:

- If a participating company/APME member covers the process step, this data source was used in the study.
- If a participating company does not cover the process step and no access to company specific data is available then information from the literature was used in the study.

5.2.3.2 Specific data sources and quality

The data used in the calculations leading to the results reported here have been derived from three main sources.

1. Information on plastics manufacturing operations has been taken from the LCA database of APME. These data are supported and have been reviewed by the industry associations concerned. A high degree of reliability is assumed and no further checks were made.
2. Information on the production of fuels, energy, transportation and materials is derived from GEMIS (Globales Emissions-Modell Integrierter Systeme (Version 4.0)). This is a publicly sponsored database and software tool. A high degree of reliability is assumed and no further checks were made.
3. Data on the production and recycling processes of the specific plastic parts of the ELV has been supplied for different plants. Information from plant managers has been checked extensively for plausibility, completeness and for representativeness. A review by the plant managers in face-to-face discussions was performed. A high degree of reliability is assigned to these data. To provide as consistent a picture as possible, all data are supplied for 2001 or for a period that provides current and sufficiently representative process data. This ensures that the data is consistent and reflects current data of the processes considered.

Table 5.2 Data sources

Data use/process			
Data specification	**Data source**	**Data description**	**Data quality**[1]
General data - transportation			
Distances	Literature, company specific data, estimations	German data, valid for the situation in Europe.	Secondary derived data[8] from simplified LCA, rough estimation
Emission data	GEMIS 2001	LCA software tool, German data valid for EU-15	Validated data
General data - energy production			
Electricity,	GEMIS 2001	LCA software tool, data	Secondary,

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[8] Data derived from more than one source.

W.European grid		valid for Europe	derived data
Process heat	GEMIS 2001	LCA software tool, German data valid for EU-15	Secondary, derived data
General data - material production			
(Auxiliary) materials used in recovery options	GEMIS 2001	LCA software tool, German data valid for EU-15	Secondary, derived data
Recovery option – landfill			
Shredder	R-plus 2001	German data from shredder plant	Primary data: company data, unpublished
Landfill	Neuwied 1998	Calculation model for German landfill	Simplified LCA
Recovery option – waste combustion			
Waste combustion	DSD 2001	Calculation model for German waste incinerator	Detailed LCA, secondary data
Emission data from waste combustion	European Directive 2000/76/EG	European emission limits	Validated data
Recovery option – cement kiln			
Processing	R-plus 2001	Specific data from fluff processing in Germany	Primary data: company data, unpublished
Cement kiln	Heyde 1997	Average data for combustion of light weight packaging in German cement kilns	Detailed LCA
Cement kiln	Verein Deutscher Zementwerke 2001	Use of plastics from ELV in cement kilns	Information from Dr. Hauer (VDZ), Primary data
Recovery option – syngas-production			
Processing	R-plus 2001	Specific data from fluff processing in Germany	Primary data: company data, unpublished

Syngas-production	SVZ 2000	LCA data for the gasification process and specific data from SVZ	Detailed LCA
Syngas-production	SVZ 2001	Use of plastics from ELV in gasification	Information from Dr. Buttker (SVZ), Primary data
Recovery option – blast furnace			
Processing	R-plus 2001	Specific data from fluff processing in Germany	Primary data: company data, unpublished
Blast furnace	DSD 2001	General data for German blast furnace, valid for the situation in Europe	Detailed LCA
Recovery option – mechanical recycling			
Dismantling	BASF 1998	Specific data, valid for Europe	Primary data: company data, unpublished
Dismantling	Confidential	Specific data, valid for car models sold in Europe	Primary data: company data, confidential
Processing,	BASF 2001, Bayer 2002, Basell 2001, Besana 2002, DaimlerChrysler 2001, ISOPA 2002, Grannex 1998 and literature	Specific data, valid for Europe	Primary data: company data, unpublished
Recycled granules (benefit, monetary)	KI 2001	Specific data from producers in Europe (sales prices)	Primary data: company data, unpublished
Recycled granules (benefit, environmental)	APME	LCA data, European production figures	Secondary, derived data

[1] "derived data" = data from various primary sources after internal review process

Sensitivity analyses were performed on dominant influence parameters.

5.2.4 Allocation procedures

In the LCA carried out here, allocations are relevant in four aspects:

1. In some of the data records adopted from other studies, allocations have already been made. These are not explicitly stated here, but can be taken from the respective sources (APME, GEMIS).
2. Dismantling: The dismantling of several plastic parts is not independent of the removal of other parts (metal, plastic etc.). If the dismantled part is part of a consecutive operation, no allocation is made. The total impact is attributed to the target plastic part.
3. Shredder: Shredding produces mainly three fractions: ferrous scrap, heavy fraction and light fraction. The energy consumption in shredding is governed mainly by the ferrous content. For plastics it is assumed that no energy is consumed. After shredding, the light fraction is separated by wind screening. This energy demand is allocated to the plastics fraction.
4. Recovery options: These processes are multi-input/output processes. The environmental impacts of these processes are known for the mixture, but not for every single input in detail.

The next table gives an overview on performed allocation procedures.

Table 5.3 Allocated processes

Process	Characteristic	Allocated for	Allocation rule	Remarks
Dismantling	Multi-output	LCA/costs	No	Only one target identified
Shredder: separation step	Multi-output	LCA/costs	Mass	Only for separation step
Processing FLUFF	Multi-output	LCA/costs	Mass	
Recycling/Recovery options[9]				
Landfill	Multi-input	LCA/costs	Mass	Emission model
MSWC	Multi-input	LCA/costs	Composition of plastic part	Emission model
Syngas production	Multi-input	LCA/costs	Heat value	Adapted emissions and products
Cement kiln	Multi-input	LCA/costs	Heat value	Adapted emissions
Blast furnace	Multi-input	LCA/costs	Heat value	Adapted emissions

Generally, the allocation of energy demands and auxiliary materials (i.e. electricity demand for processing of fluff or wind screening after shredding, fuel demand for waste pre-treatment at the landfill site) is performed according to the **mass** of the plastic part.

The amount of flue gas from waste combustion is allocated according to the **composition** of the plastic part in question (amount of C, N, S). The direct CO_2

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[9] For detailed description of the recovery processes see Annex-I.

emissions resulting from the combustion process in either a MSWC or cement kiln are allocated according to the amount of carbon in the plastic part.

Within energy processes allocation according to the **heat value** is applied. Thus electricity and heat resulting from the waste combustion in the MSWC are allocated according to the heat value of the plastic part in question. The production of methanol and energy from the syngas production process, replaced energy carriers in the blast furnace or cement kiln are allocated in the same way.

Details of the allocation in the various options are given in the Annex.

5.2.5 Selection criteria for Input/Output flows

The selection criteria for input and output flows are:

1. For **data** taken from **existing databases** (APME, GEMIS): The respective authors have determined the selection criteria and no changes have been introduced within this study. Both data records supply the necessary set of resources and emissions for the selected impact categories.
2. For **data on core processes** evaluated within this study the selection criteria has been set as less than 1% of the total input or output respectively.

5.2.6 Environmental indicators

The inventory data of the life-cycle inventory have been selected by taking into account

- Relevant environmental impacts caused by the systems under investigation
- The comparability and symmetry of the regarded systems.

Furthermore, the data availability and data quality are relevant.

Table 5.4 shows the regarded data of the inventory analysis and the responding impact categories of the impact assessment.

Table 5.4 Inventory data and impact categories

Resources	**Energy Consumption**
oil	coal
gas	oil
coal	gas
lignite	hydro
limestone	nuclear
bauxite	lignite
iron ore	biomass
sodium chloride	wind
sand	others
sulphur	
water	
others	
Airborne Emissions	
global warming potential	**acidification potential**
N2O	NH3
CO2	HCl
CH4	HF
HFC	SO2
PFC	NOx
SF6	H2S
formation of photooxidants	**catalytic stratospheric ozone depletion**
NMVOC	HCFC
CH4	CFC
Waterborne Emissions	
COD	
BOD	
N-total	
NH4	
PO4	
absorbilble organo-chlorine	
Wastes	
municipal waste	
hazardous waste	
industrial waste	
overburden/construction waste	

5.3 Life Cycle Inventory

Input data and results for the basic scenario for the example "bumpers" are shown in this section. For the other parts the input data and results are presented in the Annex.

5.3.1 Input Data for basic scenarios

The following table shows the input data for the options. In the columns "input data" specific data is shown. In the last two columns the effective mass and energy flow per part is displayed.

Table 5.5 Input data for scenario “bumper”.

			Dimension/environment			
Proces			input data		per part	
	Weight		3.14	kg/part	3.14	kg
Mechanical recycling - manual dismantling of the bumper.						
	Transportation		50	km	50	km
	Dismantling					
		Mass extracted	1		3.14	kg
	Processing		1	kg		
		Electricity	0.23503	kWh/kg	0.74	kWh
		Thermal	0.20671	kWh/kg	0.65	kWh
		Diesel	0.003	l/kg		
		Efficiency	0.88		0.88	
	Compounding		0.88	kg	2.76	kg
		Electricity	0.15	kWhel/kg	0.41	kWhel
		Thermal				
		Efficiency	1		1	
	Transportation		400	km	400	km
	Recycled granules		0.88	kg	2.76	kg
	Residues (to waste incineratio		0.12		0.38	kg
Landfill						
	Transportation		50	km	50	km
	Shredder		0.00727	kWh/kg	0.023	kWhel
		Efficiency	1		3.14	kg
	Transportation		35	km	35	km
	Landfill				3.14	kg
Energy recovery (cement kiln);						
	Heating value (upper)		43.2803	MJ/kg	135.9	MJ
	Transportation		50	km	50	km
	Shredder (Electricity)		0.00727	kWh/kg	0.023	kWh
		Efficiency	1		3.14	kg
	Transportation		100	km	100	km
	Processing		290	kWh/4t	0.22765	kWh
		Efficiency	0.95		2.983	kg
	Transportation		600	km	600	km
	Shredder residue derived fuel				2.983	kg
	Waste incineration (municipal)		0.05	kg	0.157	kg

Table 5.5 continued

Raw material recycling (synthesis gas production, SVZ)					
	Heating value (upper)	43.2803	MJ/kg	135.9	MJ
	Transportation	50	km	50	km
	Shredder (Electricity)	0.00727	kWh/kg	0.023	kWh
	Efficiency	1		3.14	kg
	Transportation	100	km	100	km
	Processing; electricity	290	kWh/4t	0.23	kWh
	Heating (Natural Gas)	0	l/h	0	l
	Efficiency	0.95		2.98	kg
	Compacting Electricity	0		0	
	Transportation	600	km	600	km
	Shredder residue derived fuel	0.95	kg/kg input	2.98	kg
	Gatefee recycled material				
	Waste incineration (municipal)	0.05	kg/kg input	0.16	kg
Municipal waste incineration					
	Transportation	50	km	50	km
	Shredder	0.00727	kWh/kg	0.023	kWhel
	Efficiency	1		3.14	kg
	Transportation	50	km	50	km
	Waste incineration (municipal)			3.14	kg
Raw material recycling (blast furnace)					
	Heating value (upper)	43.2803	MJ/kg	135.9	MJ
	Transportation	50	km	50	km
	Shredder (Electricity)	0.00727	kWh/kg	0.023	kWh
	Efficiency	1		3.14	kg
	Transportation	100	km	100	km
	Processing; electricity	290	kWh/4t	0.23	kWh
	Heating (Natural Gas)	0.0	l/h	0.0	l
	Efficiency	0.95		2.98	kg
	Transportation	600	km	600	km
	Agglomeration (Electricity)	200	kWh/t	0.60	kWh
	Efficiency	0.945		2.82	kg
	Shredder residue derived fuel	0.89775		2.82	kg
	Waste incineration (municipal)	0.10225	kg/kg input	0.32	kg

5.3.2 Results for basic environmental indicators

The results from the calculations are presented in the following table. Positive values indicate net emissions while negative values result from balancing emissions from activities with credits.

The table shows the energy consumption, the raw material use, airborne emissions, emissions from the water pathway (after treatment) and waste.

Table 5.6 Results of the Life-Cycle-Inventory of bumper.

Fuel	*Unit*	*Landfill*	*Waste Incine.*	*Cement kiln*	*Syngas-product.*	*Blast furnace*	*Mechan. recycling*
Coal	MJ	0.22	-9.41	-61.54	-15.52	-0.33	-2.77
crude oil	MJ	0.77	-3.57	3.79	-9.95	-138.66	-112.27
Natural gas	MJ	0.14	-59.44	-2.97	-122.70	-10.05	-89.96
Hydro	MJ	0.04	-2.10	-0.07	-2.50	0.05	-1.21
Nuclear	MJ	0.39	-19.49	-0.83	-25.90	0.60	-2.98
Lignite	MJ	0.08	-4.67	-71.99	-7.39	-0.41	0.44
Wind	MJ	0.00	-0.08	-0.01	-0.12	0.00	0.01
Biomass	MJ	0.00	-0.17	-0.03	-0.29	-0.02	-0.15
other	MJ				2.73		2.13
Material							
Water	kg	0.35	-17.12	-57.69	23.21	-0.01	2.27
Coal	kg	0.01	-0.34	-2.24	-0.56	-0.01	-0.09
Crude oil	kg	0.02	-0.09	0.09	-0.23	-3.47	-2.48
Natural gas	kg	0.00	-1.33	-0.07	-2.48	-0.22	-1.81
Lignite	kg	0.01	-0.54	-8.32	-0.85	-0.05	0.06
Limestone	kg	0.00	-0.02	-0.01	-0.08	0.00	0.00
Sodium chloride	kg	0.00	0.00	0.00	0.00	0.00	-0.01
Sulphur	kg	0.00	0.00	0.00	0.00	0.00	0.00
Sand and gravel	kg	0.00	-0.01	0.00	-0.05	-0.01	0.00
Bauxite	kg	0.00	0.00	0.00	0.00	0.00	-0.01
Iron ore	kg	0.00	-0.02	0.00	-0.11	-0.01	0.01
Air emissions							
CO2	mg	98831	5219466	-2726598	686544	-268992	-3519098
SOX	mg	237	-3647	-636	-17829	-7669	-33600
NOX	mg	572	5945	2123	-25006	-3348	-21778
CH4	mg	161	-17456	-29456	-55022	-11632	-16706
Halogenated HC	mg				0.00		-0.23
NH3	mg	0.24	35.35	3.27	3.85	5.73	5.50
N2O	mg	3.59	-145.00	-340.12	-123.87	-20.12	52.21
HCl	mg	5.62	429.29	-168.96	-313.01	54.35	71.69
NM-VOCs with r	mg	89.01	-568.33	430.38	-340.60	-1643.59	431.92
NM-VOCs withou	mg		3.22	0.16	-5249.56	0.33	-6470.85
HF	mg	0.50	46.10	-4.96	-22.91	5.97	9.61
H2S	mg	0.00	-0.10	-0.01	-0.42	-0.01	-4.11
PFC	mg	0.00	-0.01	0.00	-0.02	0.00	-1.95
HFC	mg						
HCFC's	mg						
SF6	mg						

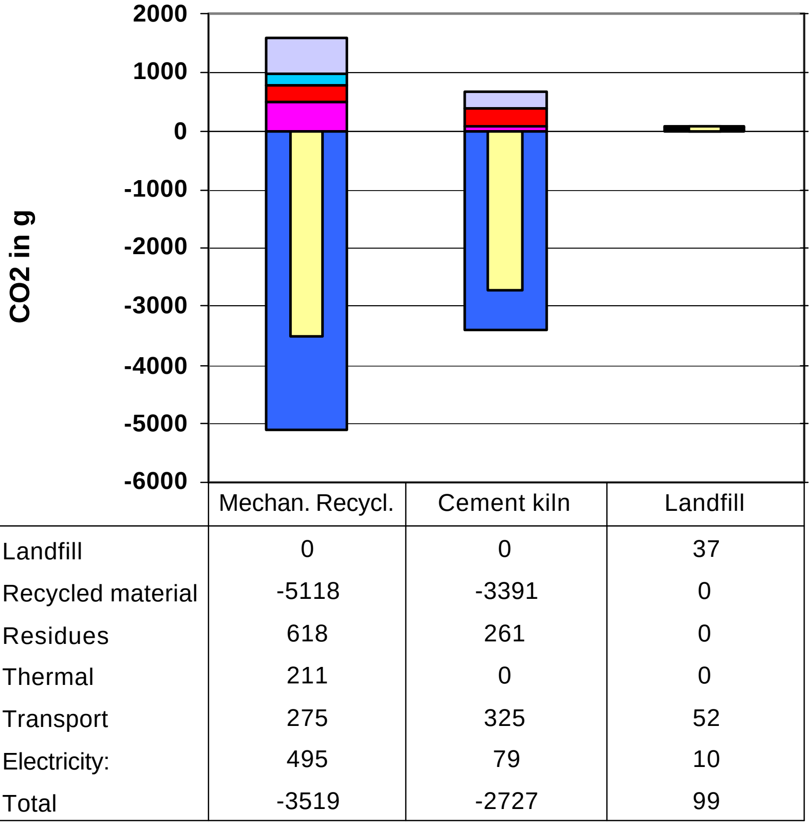
Table 5.6 continued

Water Emissions							
COD	mg	434.5	1653.0	241.3	365.7	-130.3	-40.1
BOD	mg	1.2	46.5	6.8	-40.8	-3.6	-81.0
N-tot	mg	564.7	0.0	0.0	159.9	0.0	-44.6
NH4	mg	725.6	0.0	0.0	-0.8	0.0	-26.3
PO4	mg P	0.0	0.0	0.0	-1.4	0.0	-4.0
AOX	mg	0.0	0.0	0.0	0.3	0.0	0.0
Heavy Met	mg				0.5		-1.3
HC	mg				212.0		-154.4
SO4--	mg	15706.9	0.0	0.0	-0.1	0.0	-155.1
Cl-	mg	22700.7	0.0	0.0	1593.5	0.0	-3474.9
Solid waste							
Overburden/const	kg	0.07	-3.95	-54.44	-6.06	-0.33	0.49
Municipal waste	kg	3.14	-0.23	-0.17	-0.28	-0.01	0.01
Industrial waste	kg						
hazardous waste	kg		0.00	0.00	0.00	0.00	-0.03

For energy consumption “landfill” shows small positive amounts whereas the other options have almost negative values. This results from credits by fuel or material substitution. The same effect occurs for material use.

For emissions the data results from emissions of auxiliary energy, plastic combustion (oxidation) and the corresponding credits. If the combustion of conventional fuel is less carbon dioxide intensive, a positive value occurs. For mechanical recycling, the credits for saved virgin materials dominate the figure.

The next figures show the breakdown of carbon dioxide (CO_2) emissions and nitrogen oxide emissions for three typical processes: landfill with no energy recovery, cement kiln as a typical recovery installation and mechanical recycling.



	Mechan. Recycl.	Cement kiln	Landfill
Landfill	0	0	37
Recycled material	-5118	-3391	0
Residues	618	261	0
Thermal	211	0	0
Transport	275	325	52
Electricity:	495	79	10
Total	-3519	-2727	99

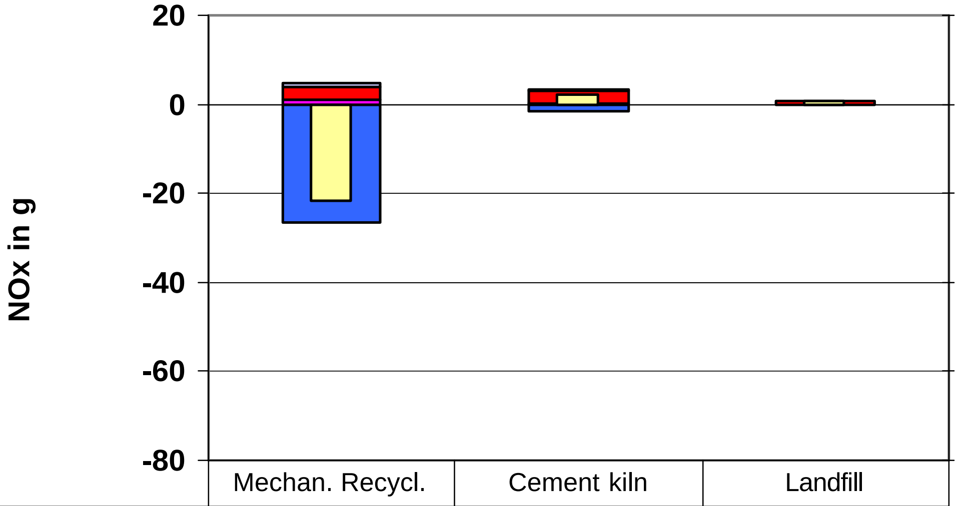
Figure 5.8 **CO_2 emission of mechanical recycling, cement kiln and landfill for bumper, disaggregated to important process steps**

Mechanical recycling: The detailed breakdown shows the high credit for the avoided production of virgin plastics. The most important other contributions to the total CO_2 emissions are electricity production and combustion of the residues (material, that is not converted to recycled material). For the processing steps the net balance is negative. This means that the overall CO_2 emission is reduced.

Cement kiln: Overall a negative emission of CO_2 is recorded. In the cement kiln itself a reduction of the CO_2 emissions is observed versus the emissions from the operation with coal as fuel. But there are additional CO_2 emissions from the plastics processing. The credit from the kiln operation outweighs the emissions from the processing of the plastics and thus a negative emission occurs.

Landfill: The operation of the dumpsite and transports lead to CO_2 emissions. No credit can be given, thus a net emission is obvious.

Overall: In the options “mechanical recycling” and “cement kiln”, the CO_2 emissions are reduced versus the reference process (production of virgin plastics, coal input). The other disposal option (landfill) shows net CO_2 emissions.



	Mechan. Recycl.	Cement kiln	Landfill
⬜ Landfill	0.0	0.0	0.1
🟦 Recycled material	-26.5	-1.3	0.0
⬜ Residues	0.6	0.3	0.0
🟦 Thermal	0.3	0.0	0.0
🟥 Transport	2.5	3.0	0.5
🟪 Electricity:	1.2	0.2	0.0
🟨 Total	-21.8	2.1	0.6

Figure 5.9 NO_X emission of mechanical recycling, cement kiln and landfill, disaggregated to important process steps for the example bumper.

Mechanical recycling: The detailed breakdown shows the high credit for the avoided production of virgin plastics. The emissions from processing of the recycling plastics are comparable small. The net balance is negative, this means, the overall NO_x – emissions are reduced.

Cement kiln: A small credit for the NO_X emissions is recorded due to avoided coal input and thus the avoidance of NO_X emissions from coal production. This is overcompensated by NO_X emission from transport and processing. Overall a net emission is observed.

Landfill: Transports and the operation of the dumpsite lead to NO_X emissions. No credit is given, thus a net emission is the result.

Overall: Due to high credits for NO_X emissions, mechanical recycling exhibits a net reduction of NO_X emissions. Cement kiln and landfill show an increase in NO_X emissions.

The results for mechanical recycling show high credits. For blast furnace, cement kiln and syngas production the credits are still significant but lower. Landfill exhibits no credits. For a more comprehensive presentation the data need further aggregation. The aggregation steps are explained in the next chapter.

5.4 Impact Assessment

5.4.1 Choice of impact categories

The results of the inventory analysis were evaluated in the impact assessment. Categories considered are:

- Energy consumption
- Resource depletion
- Global warming potential
- Acidification potential
- Photochemical ozone creation potential
- Water pollution
- Waste production

The categories selected are based on a sound scientific basis and are well accepted by most LCA experts. The category “Stratospheric ozone depletion potential” is not included because of severe data gaps. No relevant process emissions are known with respect to the core processes named in the flow sheets in Section 5.2.

The category “nutrification” is not included as a single impact because of a lack of data and methodology. The water emissions of nitrogen and phosphorous are included in the category “water pollution”.

5.4.1.1 Energy consumption

Energy consumption is calculated as the sum of all energy carriers. A detailed breakdown into different fuels and feedstock, renewable and non-renewable resources is already evaluated at the inventory stage. Note that the consumption of fossil fuels is additionally evaluated in the category “resource depletion”.

5.4.1.2 Resource depletion

Resource depletion is calculated for all inputs into the system designed by Jensen (Jensen 1996). All resource depletion (non-renewable energy carriers and mineral resources) are accounted for in one category indicator. All resources and fossil energy carriers are traced back to their extraction as minerals from the earth. The depletion of these mineral resources is measured in terms of years of reserves. Note that renewable resources, such as wood from sustainable forestry, leads to no resource depletion and thus an assessment factor of zero is assigned.

Definition of the characterization factors:

Characterization factor = 1000/reserves in years

Table 5.7 Abiotic resource depletion, characterization factors

Abiotic Resource Depletion			
Raw material	**Resources [years]**	**Characterization Factor**	**References**
Coal	160	6	Roempp
Iron	72	14	Aldershot 1994
Lignite	387	3	Aldershot 1994
Limestone	200	5	(estimated)
Natural gas	63	16	Aldershot 1994
Crude oil	42	24	Roempp
Sodium Chloride	1000	1	(estimated)
Sulphur	53	19	(estimated)
Clay	1000	1	(estimated)
Uranium	58	17	Aldershot 1994

5.4.1.3 Global warming potential

Due to their effect on infrared radiation, certain gases in the atmosphere including carbon dioxide, methane and water have an impact on the earth’s climate. Additional releases of these man-made “greenhouse” gases may lead to an increase in global temperature. A significant global warming or “greenhouse effect” is believed to occur. The contribution of air emissions to the anthropogenic global warming effect has been evaluated (IPPC 1995). The indicator is 1g of carbon dioxide equivalent (g CO_2). CO_2 from renewable energy resources (biomass) does not contribute to the global warming potential, if biomass is used under sustainable conditions, e.g. CO_2 emissions from biomass are outbalanced by CO_2 bonding of newly grown biomass.

Table 5.8 Contribution to the anthropogenic global warming potential: equivalency factors (IPPC 1995).

Global warming equivalents		
21	g CO_2	per g methane
1	g CO_2	per g CO_2
310	g CO_2	per g N_2O

Minor importance in this study: SF_6

5.4.1.4 Acidification potential

The source of potential acidification is by definition the production of protons. All air and waterborne emissions of the system were therefore examined for their potential to produce protons. Because the probability of finding waterborne proton acceptors is very small, no neutralization effect is taken into account (UBA 1995). The indicator is 1 mol of sulphur dioxide equivalent (mol SO_2).

Table 5.9 Contribution to the acidification potential: equivalency factors.

Acidification equivalents		
0.0000156 (= 0.001	mol SO_2 g SO_2)	per mg SOx (1 mol SO_2 =2 mol H^+)
0.0000109 (= 0.0007	mol SO_2 g SO_2)	per mg NOx (1 mol NO_x = 1 mol H^+)
0.0000293 (= 0.0019	mol SO_2 g SO_2)	per mg NH_3 (1 mol NH_3 = 1 mol H^+)
0.0000137 (= 0.0009	mol SO_2 g SO_2)	per mg HCl (1 mol HCl = 1 mol H^+)
0.0000257 (= 0.0016	mol SO_2 g SO_2)	per mg HF (1 mol HF = 1 mol H^+)

5.4.1.5 Formation of photo oxidants

(Photochemical ozone creation potential, POCP)

Photochemical ozone formation is caused by degradation of organic compounds (VOC) in the presence of light and nitrogen oxides (NO_X) (“summer smog” as a local impact factor and “tropospheric ozone” as a regional impact factor). The biological effects of photochemical ozone can be attributed to biochemical effects of reactive ozone compounds. Exposure of plants to ozone may result in damage to leaf surfaces, leading to damage to the photosynthetic function, discolouring of leaves, dieback of leaves and finally the whole plant. Exposure of humans to ozone may result in eye irritation, respiratory problems and chronic damage to the respiratory system.

Photochemical ozone formation can be quantified by using the photochemical ozone creation potential (POCP) for organic compounds. POCPs for organic compounds are expressed as ethene (C_2H_4) equivalents, i.e. their impacts are expressed relative to the effect of C_2H_4 (UBA 1995).

Table 5.10 Contribution to the photochemical ozone creation potential: equivalency factors.

Ethene equivalents		
0.007	g ethene	per g methane
0.416	g ethene	per g alkane

There are some limitations in interpreting the results for the formation of photo oxidants (Heyde 1999). A range of conditions which, as a rule, are not comprised in the inventory data influences the formation of ground level ozone. Ascertaining this indicator is subject to even more vagueness than is the case with the other emission potentials (e.g. global warming potential). In spite of these limitations, the authors decided to include this impact category.

5.4.1.6 Water emissions

Table 5.11 Contribution to water emissions: equivalency factors.

Water emissions, critical volumes method, dilution factors applied		
Parameter	Dilution factor (l/mg)	Annex to German waste water regulation (Ref. Abwasserverordnung 1997).
COD	1	No. 1
BOD	5	No. 1
Total N	4	No. 1
NH_4	8	No. 1
PO_4	75	No. 1
AOX	75	No. 9
Heavy metals	75	No. 9
Hydrocarbons	38	No. 45

Legend for the above table

COD: Chemical oxygen demand: BOD: Biological oxygen demand: Total N: Total nitrogen: NH_4: Ammonium ions: PO_4: Phosphate ions: AOX: Absorbable organic halogens

Water emissions are calculated as critical volume. For every emission a volume of water is calculated, which is necessary to ensure sufficient dilution to an acceptable effect level in the environment. The acceptable levels for the calculations in this study are based on the German legislation “Abwasserverordnung” (waste water regulation from 1997). These limit values are based on environmental relevance, although in some cases the definition of the limit values is additionally driven by technical arguments. Despite this limitation, we prefer this system because of:

- Complete database for most relevant emissions
- Accepted by relevant industry associations and legal authorities
- Well known to practitioners in industry

5.4.1.7 Waste production

No physical law gives guidance for the evaluation of equivalency factors. Monetary values have been chosen as the basis for aggregation of the different types of waste. Costs are considered as a good indicator of the relative “dangerousness” of different types of waste as it reflects the measures required for adequate containment. The cost figures given in the table are taken from “state-of-the-art” landfills. Nevertheless, the cost figures can vary widely because local geological parameters have a high influence on the costs. For these reasons the differences might be even higher than the figures shown in the table. The indicator is 1 kg of waste. Based on expert judgment we derived the following parameter set:

Table 5.12 Equivalency factors for waste.

Waste production	
Waste category	equivalency factors
Mineral waste, rubble	0,2
Domestic waste, ashes & slags	1
Hazardous waste	5
Industrial waste	5
MSWC Ash	5
Flue gas cleaning sludge	5
Sewage	5

The categories selected are based on a sound scientific basis and are well accepted by most LCA experts.

5.5 LCA Results

5.5.1 LCA Results for “bumpers“

The results of the LCI for bumpers after the impact assessment are shown in the next table. The results of the other plastic parts are in the Annex.

Table 5.13 Results of environmental impacts for the example “bumper“.

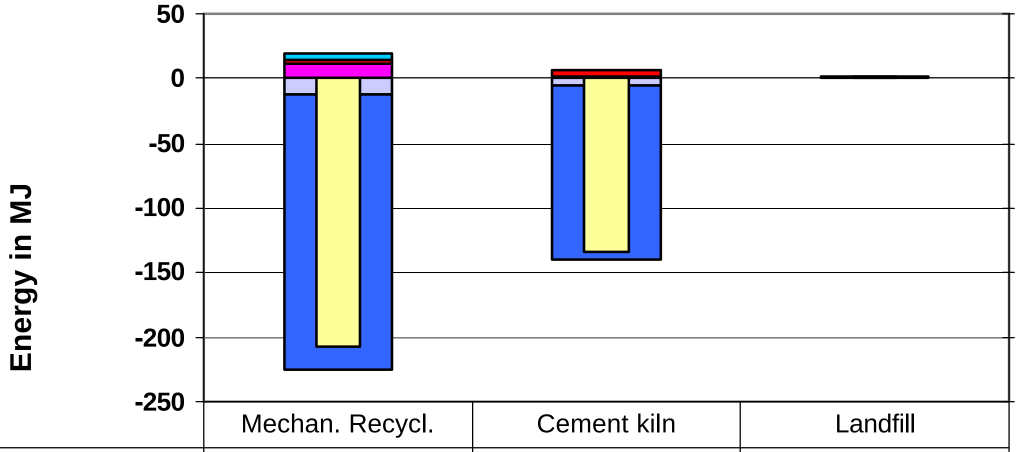
Recycling options		Landfill	Waste Incin-eration	Cement Kiln	Syngas-production	Blast furnace	Mech. Recycling
Category							
Raw material use	in kg/a*1000	0.6	-27.0	-34.2	-52.4	-86.5	-88.1
Energy consumption	in MJ	1.7	-98.9	-133.7	-181.6	-148.8	-206.8
Emissions							
Air							
GWP	in g CO2 -equiv.	103	4808	-3451	-507	-520	-3867
POCP	in g ethene-equiv.	0.04	-0.36	-0.03	-2.71	-0.77	-2.63
AP	in g SO2 -equiv.	0.6	1.0	0.7	-35.6	-9.9	-48.8
Water	Critical volume in m^3	148.2	25.1	3.7	117.9	-2.0	-97.2
Waste	normalized mass	3.15	-1.02	-11.05	-1.49	-0.08	-0.05

The raw material considered in the option “landfill” shows a small positive, in the others a negative result. “Landfill” is “consuming” material for disposal. The other options are producing or substituting material and a credit is given resulting in a negative raw material use. Material use for disposal or process operation has only a slight influence on the results.

The energy consumption shows a figure similar to that for raw material use. The options can be classified in four categories: “landfill” with a small energy consumption, “waste combustion” with a low energy efficiency and corresponding low credit, “cement kiln”, “syngas production” and “blast furnace” with a high energy efficiency and high credit and “mechanical recycling” with a high credit from substitution of virgin plastics. The different ranking between the category “raw material use” and “energy consumption” results from the different types of energy carrier or raw material used by the various options.

For the sake of easier presentation, only three processes are highlighted in the next figure, namely: landfill, cement kiln and mechanical recycling. Cement kiln is seen as representative for energy recovery processes.

A detailed disaggregation of the energy consumption is shown in the next figure.



	Mechan. Recycl.	Cement kiln	Landfill
⬜ Landfill		0.0	0.7
🟦 Recycled material	-213.3	-135.0	0.0
⬜ Residues	-12.0	-4.9	0.0
🟦 Thermal	3.4	0.0	0.0
🟥 Transport	3.8	4.5	0.7
🟪 Electricity:	11.3	1.8	0.2
🟨 Total	-206.8	-133.7	1.7

Figure 5.10 Energy consumption of mechanical recycling, cement kiln and landfill, disaggregated to important process steps, for the example bumper.

Mechanical recycling: The detailed breakdown shows the high credit for the avoided production of virgin plastics. Additionally a smaller credit is given to the combustion of the residues (material that is not converted to recycled material). Some energy is consumed for the electricity used for plastics processing. The credits outweigh the energy consumption by far and a net energy credit is recorded.

Cement kiln: In the breakdown the high credit for the avoidance of coal combustion is dominant. Additionally, a small credit is given to the combustion of the residues (material that is not converted to recycled material). Some energy is consumed for the electricity used for plastics processing. The credits outweigh the energy consumption by far and a net energy credit is recorded.

Landfill: The operation of the dumpsite and transports lead to energy consumption. No credit can be given, thus net energy consumption is obvious.

Overall: Mechanical recycling and to a reduced extent the combustion of plastics in the cement kiln can save energy versus landfill.

For the **Global Warming Potential** (GWP) positive and negative values occur. Positive values indicate a net emission of greenhouse gases whereas negative values indicate a reduction with respect to the substituted materials. “Waste combustion” shows a positive emission value[10]. Beside emissions from auxiliary inputs, this means that the combustion of plastic parts is less efficient concerning greenhouse gases than the credited processes.

The **Photo Oxidants Creation Potential** (POCP) shows negative values for the most options. Substituting fuels results in savings during the extraction of conventional fuels, which show significant emissions of POCPs.

In the **Acidification Potential** (AP) nitrogen oxides and sulphur oxides make up the main contributors. The main emissions result from transport operations. In most options these emissions are counteracted by saved emissions from conventional fuel extraction and their corresponding transports.

“Landfill” has **water discharges** during operation. For “mechanical recycling” negative values are presented because of credits from virgin material production. For the other options small amounts are balanced mainly resulting from process operations.

Waste mainly originates from waste disposal (“landfill”, “mechanical recycling” for side stream) or from process operations. In the “syngas production” options lignite is substituted which would produce significant amounts of waste.

Some preliminary conclusions may be drawn already at this stage:

1. The main drawbacks of landfill are energy pollution, water pollution and waste.
2. The main drawback of waste combustion is global warming.
3. The other four options show balanced advantages and drawbacks.

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[10] Electricity production is less CO2 intensive due to the higher efficiency in conventional plants and nuclear power.

5.6 LCA sensitivity analysis “Total Life”

In addition to the LCA base scenario on recovery options this LCA is enlarged to total life. The functional unit includes the production, use and end-of-life treatment. This sensitivity analysis is performed to explore the relative importance of the recovery steps in the overall life cycle of an automobile.

The LCA “Recovery Options” is strongly linked to the ELV Directive. The main objective is the question of recycling/recovery targets, the recycling options and their environmental benefits. In political terms this LCA refers to the “waste view”. The decision making process is linked to the disposal of ELV as covered by the system boundaries in base scenario. If production and use phase is added, as in the LCA “total life”, the objective changes to a “product view” and the total life is included in the LCA. This sensitivity analysis should highlight the relevance of the recovery processes in the base scenario with respect to the environmental effects of their total life.

In comparison to the LCA base case on “recovery options” the LCA on “total life” shows the following differences:

Goal

The goal of the analysis is to highlight the relevance of the base scenario “recovery options” with respect to the total life of the discrete plastic parts.

Functional Unit

The Functional Unit is defined as:

> The production, use and treatment of 1 kg of discrete plastic parts in vehicles

System boundaries

A scheme showing the differences in the system boundaries of the two LCAs is in the next graphic.

The following individual process steps are added to the base scenario:

1. Production: the production of plastic parts by automobile supplier
2. Assembly of the car: the assembly of plastic parts into the vehicle (by the manufacturer)
3. Use: use of the vehicle (150,000 km)

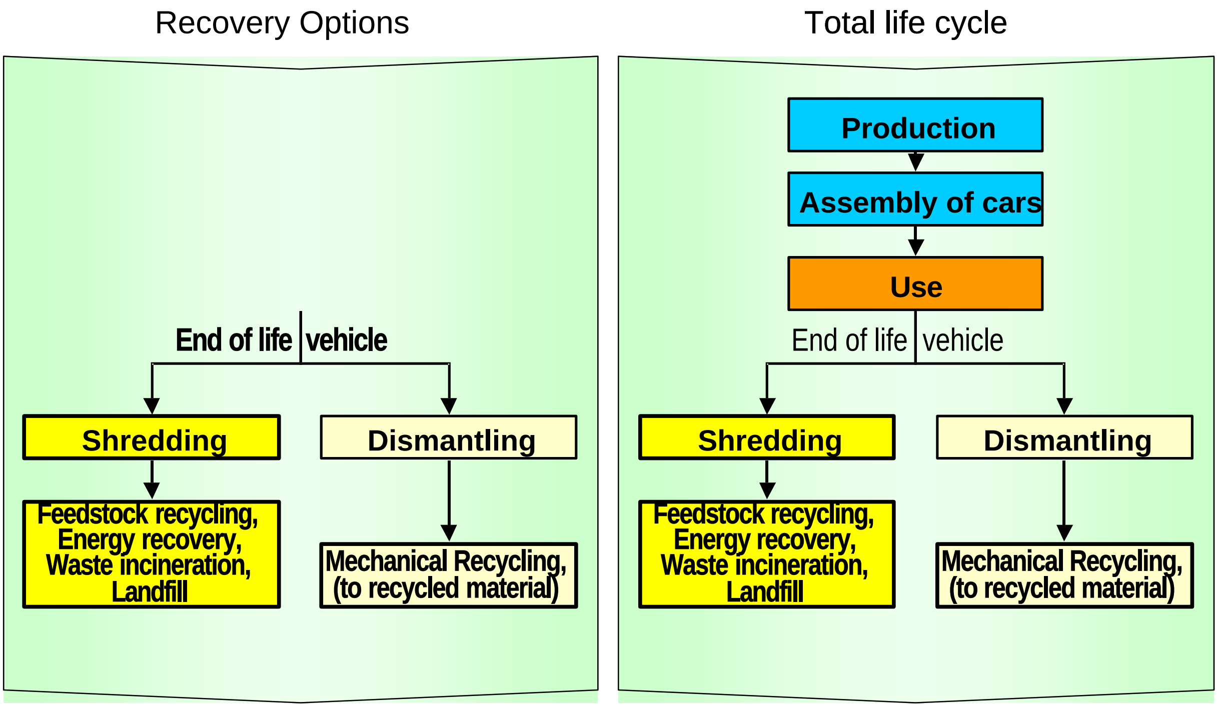


Figure 5.11 Comparison of LCAs (recovery options vs. total life) and the process steps included.

5.6.1 Input Data

Production:

Data on production for plastic parts have been supplied by manufactures. Starting from the raw material, compounding, moulding and transport to the automobile manufacturer is included.

Use

The impact of the parts is characterized by their additional weight they are contributing to the total weight of the automobiles. Depending on the mode of driving, the weight of the car together with rolling resistance and air resistance are the main factors determining the energy demand. In this study an average contribution by weight of 0.35 litres gasoline per 100kg weight per 100km driving distance is set. It was assumed that the weight reduction is part of the design phase of the car and is accompanied by constructional changes (e.g. gear ratio change). The fuel consumption figures given here could not be used to estimate the additional fuel consumption for an extra load of an existing car.

An overview of different sources is given in the following table.

Table 5.14 Fuel reduction values in the literature

Average in l/(100 kg*100 km)	Range l/(100 kg*100 km)	Source	Remark
0,38	0,19 – 0,6 (gasoline) 0,26 – 0,37 (diesel)	EUCAR 1997	Average of several producers. Includes gear ratio change.
----	0,34 – 0,48 (gasoline) 0,29 – 0,33 (diesel)	Eberle 1998	Different BMW models. Includes gear ratio change.
0,35	---	FhG-IVV 1999	Experience of car manufacturers experts. Includes gear ratio change.
0,35 minimal	0,35 – 0,85	Saur NYb	Experience report submitted by ADAC
This study			
0,35	---		

The additional input data is summarized in the following table.

Table 5.15 Additional input data for production and use phase for bumpers.

Process			Dimension/environment			
			input data		per part	
Production						
	Weight		3,14	kg	3,14	kg
	Raw material					
		Granules PP-40%TV	3,14	kg	3,14	kg
	Transportation					
		20-tons load	200	km	0,628	t*km
	Injection moulding					
		Electricity	18	MJ/part	5	kWh
		Rejects	0		0	
	Transportation					
		20-tons load	200	km	4,4	t*km
		Effective weight per bumper incl. Packaging	22	kg		
		Number of bumper	250	pieces		
	Laquer					
		Mass	0	kg/part	0	kg
		Application electrical	0	kWh/part	0	kWh
		Application thermal	0	m^3/part	0	MJ
Use						
	travel distance		150000	km	150000	km
	additional fuel consumption		0,35	liter	16,485	liter
	per part, 100 kg und 100 km					

5.6.2 LCA Inventory Results

The following table shows the result of the “total life” sensitivity analysis. It includes the production and use phase for each option and additionally the recovery option itself. The production and use phases are the same in every option leading to an offset in comparison with the pure recovery options.

The results are dominated by the use phase. Production also has an important impact on the total values. The results from the recovery/recycling phase are of minor importance.

For fuel consumption the impact of the use phase and also production can clearly be identified. In the category fuel consumption, the crude oil consumption shows a steep increase in comparison to recovery only. This effect is mirrored for raw material use.

For air emissions an extraordinary increase of nitrogen oxides can be noticed. This is due to the specific higher emissions during combustion in road vehicles. Additionally the emission of NMVOCs from road transport also shows a sharp increase.

Table 5.16 Results for production an use phases and recovery options for bumpers.

								therefrom …	
Fuel	*Unit*	*Landfill*	*Waste Incine.*	*Cement kiln*	*Syngas-product.*	*Blast furnace*	*Mechan. recycling*	production	use
Coal	MJ	44	34	-18	28	43	41	16	27
crude oil	MJ	888	884	891	878	749	775	150	737
Natural gas	MJ	147	87	144	24	137	57	105	41
Hydro	MJ	5	3	5	2	5	4	4	1
Nuclear	MJ	33	14	32	7	34	30	27	6
Lignite	MJ	10	5	-62	2	9	10	4	5
Wind	MJ	0.1	0.1	0.1	0.0	0.1	0.1	0.1	0.1
Biomass	MJ	0.6	0.4	0.6	0.3	0.6	0.4	0.3	0.2
other	MJ	-2.4	-2.4	-2.4	0.3	-2.4	-0.3	-2.4	
Material									
Water		44	26	-14	66	43	45	18	25
Coal	kg	2	1	-1	1	2	1	1	1
Crude oil	kg	22	22	22	22	18	19	3	18
Natural gas	kg	3	2	3	1	3	1	2	1
Lignite	kg	1	1	-7	0	1	1	1	1
Limestone	kg	0.3	0.3	0.3	0.2	0.3	0.3	0.0	0.3
Sodium chloride	kg	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sulphur	kg	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sand and gravel	kg	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Bauxite	kg	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Iron ore	kg	1.5	1.5	1.5	1.4	1.5	1.6	0.0	1.5

Table 5.16 continued

Air emissions									
CO2	mg	64.7E+6	69.8E+6	61.9E+6	65.3E+6	64.3E+6	61.1E+6	8.9E+6	55.7E+6
SOX	mg	111.7E+3	107.8E+3	110.8E+3	93.6E+3	103.8E+3	77.8E+3	50.0E+3	61.5E+3
NOX	mg	131.0E+3	136.4E+3	132.6E+3	105.4E+3	127.1E+3	108.7E+3	44.2E+3	86.2E+3
CH4	mg	98.5E+3	80.9E+3	68.9E+3	43.3E+3	86.7E+3	81.6E+3	25.4E+3	72.9E+3
Halogenated HC	mg	0.26	0.26	0.26	0.26	0.26	0.0	0.3	
NH3	mg	3201	3236	3204	3205	3206	3206	5	3196
N2O	mg	4561	4412	4217	4433	4537	4609	130	4427
HCl	mg	595	1018	420	276	643	661	396	193
NM-VOCs with ro	mg	108.9E+3	108.3E+3	109.3E+3	108.5E+3	107.2E+3	109.3E+3	1.9E+3	106.9E+3
NM-VOCs withou	mg	7354	7357	7354	2104	7354	883	7354	
HF	mg	47	93	42	24	53	57	31	16
H2S	mg	5	5	5	4	5	1	5	0
PFC	mg	2	2	2	2	2	0	2	0
HFC	mg	0	0	0	0	0	0	0	
HCFC's	mg	0	0	0	0	0	0	0	
SF6	mg	0	0	0	0	0	0	0	

Table 5.16 continued

Water Emissions									
COD	mg	45.6E+3	46.9E+3	45.5E+3	45.6E+3	45.1E+3	45.2E+3	1.5E+3	43.7E+3
BOD	mg	1360	1405	1366	1318	1355	1278	132	1227
N-tot	mg	615	51	51	211	51	6	51	0
NH4	mg	755	30	30	29	30	4	30	
PO4	mg P	5	5	5	3	5	1	5	
AOX	mg	0.01	0.01	0.01	0.29	0.01	0	0	0
Heavy Met	mg	1	1	1	2	1	0	1	
HC	mg	175	175	175	387	175	21	175	
SO4--	mg	15883	176	176	176	176	21	176	
Cl-	mg	26649	3949	3949	5542	3949	474	3949	
Solid waste									
Overburden/const	kg	11.5	7.5	-43.0	5.4	11.1	12.0	3.8	7.6
Municipal waste	kg	4.1	0.8	0.8	0.7	1.0	1.0	0.3	0.7
Industrial waste	kg								
hazardous waste	kg	0.04	0.04	0.04	0.04	0.04	0.0	0.0	

5.6.3 LCA results

The next table shows the results for the “total life” of the plastic part “bumper”. Included is the production, the use phase limited to allocated gasoline consumption and the recovery pathways. The first two phases (production and use) are identical for every option.

The results clearly show the major influence of production and use on the total results. In comparison to the recovery options the total life data has changed significantly. In “total life” the raw material use for “landfill” and “mechanical recycling” show only differences of approximately 20%. The same effect occurs for energy consumption, GWP and POCP. For AP and water the differences are not so impressive. Unlike the other categories, the disposal routes rule the category “waste”.

A detailed breakdown of the categories “energy consumption” and “raw material use” according to the influence parameters “production”, “use phase” and “recovery options” is shown in the following figures.

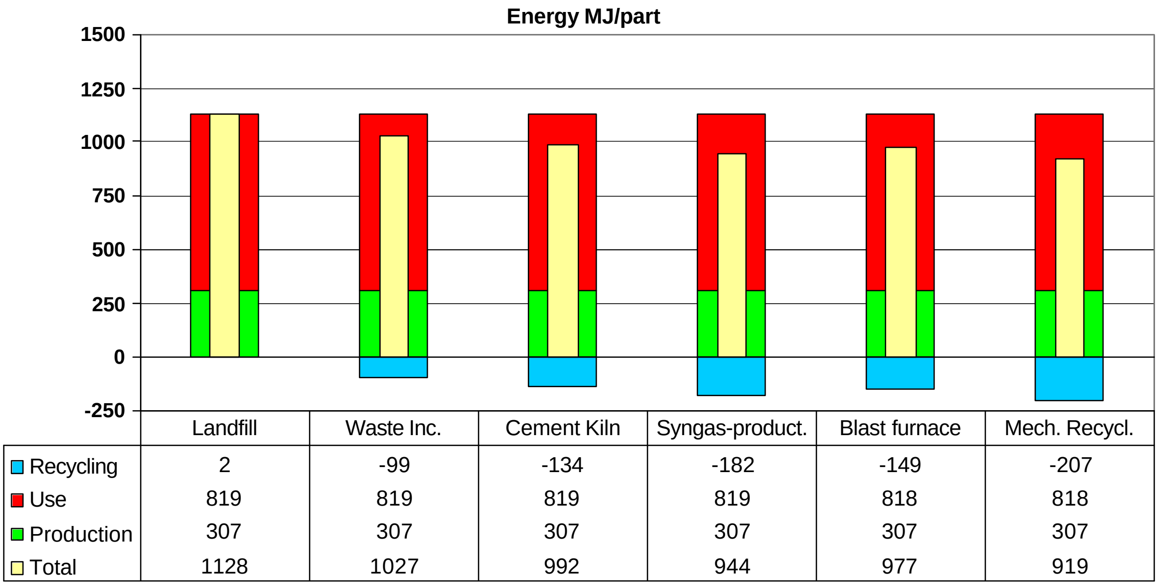
For energy consumption the total balance shows the high influence of production and use. Production accounts for approximately a third and the use phase for two thirds of the total energy consumption. Credits from the recovery option have an influence of maximum 15% on the total results.

In the category “raw material use” the effect described for energy consumption is accelerated. The energy consumptions in production and use are dominated by oil or natural gas consumption, which also have a major influence on raw material use.

As a main conclusion, the importance of the use phase for the key element “energy consumption” needs to be highlighted. Whether “design for end-of-life” or the use of ELV recyclates are implemented, the solutions should not lead to heavier cars.

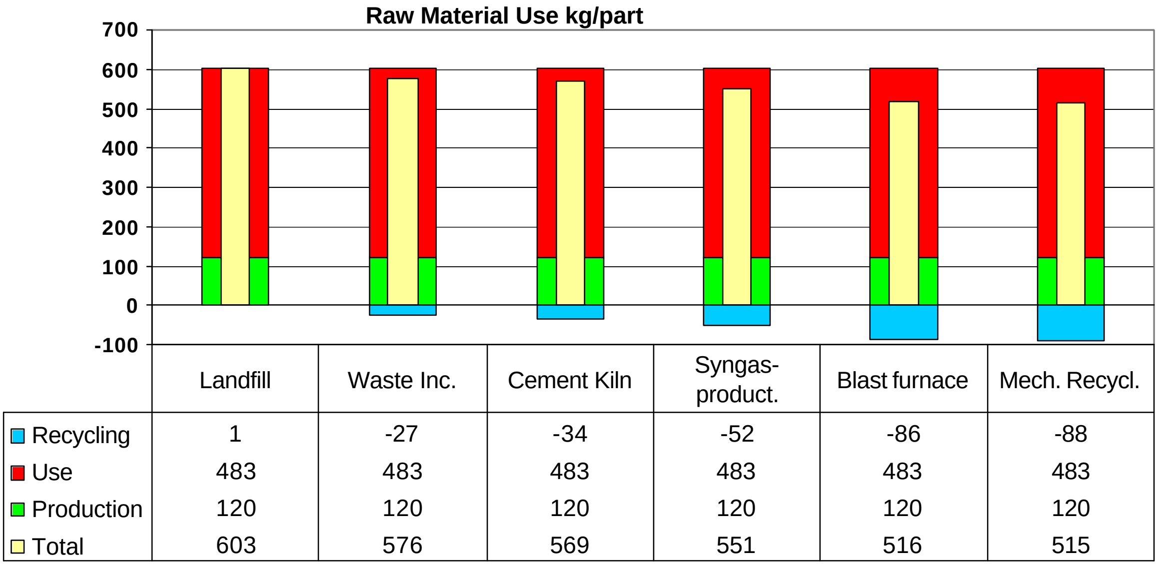
Table 5.17 LCA results for “bumpers” including production, use phase and recovery options.

Full life cycle (production, use and recycling option)		Landfill	Waste incin.	Cement Kiln	Syngas-production	Blast furnace	Mech. Recycling		Product only	Use only
Category										
Raw material use	kg/a*1000	603	576	569	551	516	515		120	483
Energy consumption	MJ	1128	1027	992	944	977	919		307	819
Emissions										
Air										
GWP	g CO_2 -equiv.	68.2E+3	72.9E+3	64.6E+3	67.6E+3	67.6E+3	64.2E+3		9.5E+3	58.6E+3
POCP	g ethene-equiv.	49	49	49	46	48	46		4	45
AP	g SO_2 -equiv.	210	210	210	174	199	161		81	128
Water	Critical volume in m^3	945	822	801	915	795	700		132	665
Waste	Weight. mass	3.2	-1.0	-11.1	-1.5	-0.1	0.0		1.2	2.3



	Landfill	Waste Inc.	Cement Kiln	Syngas-product.	Blast furnace	Mech. Recycl.
🟦 Recycling	2	-99	-134	-182	-149	-207
🟥 Use	819	819	819	819	818	818
🟩 Production	307	307	307	307	307	307
🟨 Total	1128	1027	992	944	977	919

Figure 5.12 Energy consumption for the scenario “bumper” for production, use phase and recovery options.



	Landfill	Waste Inc.	Cement Kiln	Syngas-product.	Blast furnace	Mech. Recycl.
🟦 Recycling	1	-27	-34	-52	-86	-88
🟥 Use	483	483	483	483	483	483
🟩 Production	120	120	120	120	120	120
🟨 Total	603	576	569	551	516	515

Figure 5.13 Raw material use for the scenario “bumper” for production, use phase and recovery options

6 Eco-Efficiency Analysis

6.1 Introduction

To an increasing extent, the environmental aspects of business activity are being ranked alongside the financial issues. It is against this background that BASF has developed the tool of eco-efficiency analysis to address not only strategic issues but also issues posed by the marketplace, policy and research. Predictable analysis times and costs for processing the eco-efficiency analysis are essential factors for the efficient use and effectiveness of this method. It is based on assessing environmental impacts, possible impacts on human health and ecosystems and the costs of products and processes within given system boundaries.

The term eco-efficiency was coined by Stephan Schmidheiny and coworkers[11]. The World Business Council for Sustainable Development (WBCSD) then defined eco-efficiency as a management philosophy in 1993 following the 1992 Rio summit. Business was to be encouraged to become more competitive and innovative while at the same time exercising greater responsibility for the environment[12.]

Eco-efficiency has been variously defined and analytically implemented by several workers. In most cases eco-efficiency is taken to mean the ecological optimisation of overall systems while not disregarding economic factors[13]. Eco-efficiency expresses the ratio of economic creation to ecological destruction[14]. However, the improvement of purely ecological factors, for example better utilization of resources through more efficient processes, is also frequently referred to as increased eco-efficiency[15.]

The goal of eco-efficiency analysis by the BASF method is to quantify the sustainability of products and processes using a pragmatic and flexible approach. At the same time there has to be a sound scientific background to ensure suitable reliability of the results obtained. A modular design is intended to help keep arithmetical operations transparent. As a result, ecological and economic impacts are very simple to assign to causes. This facilitates discussions with customers and data suppliers to validate the overall system and improves the testing for plausibility. Finally, the results should be made available in a form where they are easily communicable in a clear manner and provide scope for scenario assessments and discussions.

Eco-efficiency analysis includes the following working steps:

[[11] Claude Fussler, “Die Öko Innovation”, S. Hirzel Verlag Stuttgart, Leipzig, 1999, p. 127.

[12] WBCSD Congresses in Antwerp, November 1993, March 1995 and Washington, November, 1995. WBCSD: Eco-efficient leadership for improved economic and environmental performance, 1996.

[13] Ernst Ulrich von Weizsäcker, Jan-Dirk Seiler-Hausmann (Ed.), Ökoeffizienz Management der Zukunft, 1999, Birkhäuser Verlag, Switzerland, ISBN 3-7643-6069-0.

[14] K. Hungerbühler, J. Ranke, T. Mettier, Chemische Produkte und Prozesse , **1999**, Springer Verlag Berlin, ISBN 3-540-64854-2.

[15] Ciba Spezialitätenchemie, Umwelt, Gesundheit und Sicherheit - Innovationen im Umweltbereich.

1. Preparation of a specific life cycle analysis for all investigated products or processes according to the rules of ISO 14040 ff. (see Section 5, "LCA")
2. Determination of impacts on the health of people and dangers for the environment (see below "Toxicity")
3. Determination of risk potentials (see below "Risk Potential")
4. Calculation of total cost from (final) customer viewpoint (see below "cost")
5. Normalisation and weighting of life cycle analysis
6. Determination of relation between ecology and economy. To this end, the impact scores developed in the life cycle analysis are aggregated by means of an overall weighting
7. Analysis: weaknesses, assessment of scenarios, sensitivity, business options

6.2 Environmental Data

The environmental aspects covered by an eco-efficiency analysis are:

1. Energy consumption
2. Resource depletion
3. Emissions
   Air: greenhouse gases, ozone depletion, photochemical ozone creation, acidification
   Water: critical volume
   Solid waste: weighted mass
4. Toxicity potential
5. Risk potential

The first three environmental aspects are available from LCA data. The two others are included in this section.

Within the environmental categories the categories risk potential and toxic potential are integrated. In principle both categories could be part of an LCA under ISO 14040 but in practice these categories are not included[16] in standard LCAs. There is still a lack of methodology and a lack of data.. The eco-efficiency approach presented in this study covers both aspects because:

1. The approach is strongly linked to the "sustainability" concept[17], which includes risk and toxic properties.

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[16] If an impact is assumed, a "hot-spot" analysis is performed.

[17] See references above.

2. The approach is often performed for innovative products or processes. Risk reduction and the reduction of potential threats by toxic components are playing an increasingly important role in the decision-making process. Alternative chemicals are often initiated by the discussion on the toxic properties.
3. The toxic properties of products are a fundamental base of EU environmental policy and legislative action. The restriction on heavy metals in the ELV Directive serves as an example.

However the lack in methodology and the lack of data lead to the conclusion that risk potential as well as the toxic potential cannot be covered under the strict rules of LCAs. Therefore both are covered in the eco-efficiency part.

6.2.1 Toxicity potential

Many life cycle analyses do not conduct an assessment of toxicity potential. But to arrive at a comprehensive assessment of products and processes it is specifically this criterion, which constitutes an important factor with regard to the evaluation of sustainability.

Within this study, the toxicity potential deals with aspects concerning human health and environmental threats. Unfortunately, data on emissions or exposure are missing normally even for single aspects. Therefore a half-quantitative assessment has to be performed, based on expert judgement. This judgement includes the categories as well as the assessment of the processes. The following aspects have been identified:

Table 6.1 Impact categories for Toxic Potential.

Phases	**Category**	**Aspects concerning**
Production of plastic parts	**Production of chemical products**	Human- and eco-toxicity
	Particle emissions during Transport	Human toxicity
	Handling of glass fibres (plastic fillers)	Human toxicity
Use	**Benzene emissions from use of the car**	Human toxicity
Recycling/Recovery/Disposal	**Particle emissions during Transport**	Human toxicity
	Emissions or toxic or noxious substances into air during treatment	Human- and eco-toxicity
	Emissions or toxic or noxious substances into water during treatment	Human- and eco-toxicity
	Credit for fuel or material not produced	Human- and eco-toxicity

For this study only the categories for the phase “recycling/recovery” are relevant. The categories for the phase “production” are shown only for explanation of the last category in the field of “Recycling/Recovery”: Credit for fuel or material not produced.

At the present time only a semi-quantitative evaluation could be carried out. Relevant items are classified into ‘low’, ’medium’ or ‘high’. The total of this evaluation is the basis for the ranking. Low is equal to 1 point, medium 2 points and high 3 points. According to the life cycle assessment methodology avoided toxicity potential is signed with a credit.

Table 6.2 Assessment of the toxicity potential per weight for bumper.

		Landfill	Waste Inciner.	Cement kiln	Syngas-production	Blast furnace	Mechan. recycling
Production	**Production of chemical products**	2	2	2	2	2	2
	Particle emissions during Transports	1	1	1	1	1	1
	Handling of glass fibres	0	0	0	0	0	0
Recycling/ Recovery / Disposal	**Particle emissions during Transports**	1	1	2	2	2	2
	Emissions of toxic or noxious substances into air	1	2	3	1	1	0
	Emissions of toxic or noxious substances into water	3	1	0	2	0	1
	Credit for not produced fuel or material	0	-1	0	0	-1	-2

For the production phase the toxicity potential for bumpers is assessed as medium. Transport aspects are low (1). Additional fillers are not used.

Particles emissions during transport

In the recovery pathway, “landfill” and “waste combustion” are processes, which are locally available. Hence both operations will need significantly less transport than the other operations, especially if pre-treatment or single process steps are situated at different sites. Therefore “landfill” and “waste combustion” are assessed low impact (1) from transport emissions; the others are medium (2).

Emissions of toxic or noxious substances into air

The next category is toxic emissions from recovery processes. For mechanical recycling no additional emissions (not included in the LCA) could be identified. “Landfill”, “syngas production” and “blast furnace” show emissions with low impact. Assessment of landfill emissions is very uncertain and the attribution to plastics is not easy, because plastics don’t react immediately but may contribute in the future. Therefore, because the landfill’s long-term stability is not assured and physical behaviour (bad compaction properties) can lead to breaks in the body of landfills, “landfill” is attributed a low impact. “Waste combustion” is assigned a medium impact.

Plastics cause a high exhaust gas volume, which transports additional toxic chemicals into the atmosphere. In contrast to the other processes where plastic is combusted or incinerated, cement kilns have no exhaust gas treatment, which would transfer toxic substances to a waste stream. The process depends on high quality combustion, which destroys organic substances and incorporates inorganic materials into the product. Depending on the exhaust gas temperature, mercury can be present in particle-borne or vapour-form in the dust collector. To control mercury emissions, it may therefore become necessary to limit the waste related mercury input into the kiln system[18]. It is estimated that the pre-treatment step lowers the input of heavy metals to the kiln in line with the requirements of the emission standards but emissions may nonetheless occur. The assessment of a high impact reflects some uncertainty about these processes. In future a further development in pre-treatment technology may reduce these impacts.

Emissions of toxic or noxious substances into water

The path “emissions to water” is determined by the potential for short- and long-term emissions from process or disposal sites. Rain is introduced in landfills and released with toxic chemicals. As long as landfills contain a mixture of toxic and non-toxic waste the criteria for this category are the water volume and corresponding land use by disposed waste leading to water discharges. Therefore “landfill” is assigned a high impact. Syngas production has a water process stream and additionally produces waste. Both, “waste combustion” (ashes from the combustion process) and “mechanical recycling” (washing during processing of plastic parts) produce waste, which have the potential to contaminate water streams. “Cement kiln” is a process, which has no separate abatement installations and therefore no specific waste, thus no impact is

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[18] Only very small amounts of heavy metals originate from automotive plastic parts but plastic from shredders may be contaminated with heavy metals.

identified. The “blast furnace” process has a wastewater stream but this is allocated to steel making, not to the introduction of plastic to the process.

Credit for not produced fuel or material

The last criteria give credits for materials and fuels not produced. In “landfill” no fuel is saved. In “cement kilns” coal or lignite is substituted and in “syngas production” (natural) gas is substituted. Gas, coal and lignite are not classified as toxic or noxious (no R-phrase, see above). In “blast furnace” fuel oil is substituted. Fuel oil is often classified (R 45). In “waste combustion” electrical energy is produced from waste and in LCA credits are given for substitution from the electricity grid with has inputs from fuel oil and nuclear power. So a credit for a small impact is assigned. In “mechanical recycling” credits are given for not producing the primary plastic.

An explicit weighting between these four categories has not been performed because exposure routes are not known. Some exposures are potentially long lasting (water emissions from landfills) others are short (produced materials). Within this study the four categories are therefore simply added.

6.2.2 Risk potential

The parameter risk potential is an aggregation of the different risks of all levels of the process chain. The potential risk of accidents, misuse, non-directed use etc. is considered. In addition to the potential extent of the damage, the probability of occurrence is also taken into account. A semi-quantitative evaluation is carried out. Relevant items are classified into ‘low’, ’medium’ or ‘high’. The total of this evaluation is the basis for the ranking. Low is equal to 1 point, medium 2 points and high 3 points. According to the life cycle assessment methodology avoided risk is signed with a credit.

Table 6.3 Impact categories for risk potential

Production of plastic parts	**High pressure in production**	Damages to materials or persons
	High temperature in production	Damages to materials or persons
	Accidents during painting, etc.	Damages to materials or persons
	Work place accidents	Damages to materials or persons
	Transportation accidents	Damages to materials or persons
Use in vehicle	**Accidents during handling of fuels**	Damages to materials or persons
Recycling/Recovery Disposal	**Transportation/logistics accidents**	Damages to materials or persons
	Handling of highly flammable or explosive substances	Damages to materials or persons
	Disposal/long-term stability	Damages to materials or persons
	Product quality does not meet specifications	Damages to materials or persons
	Credit for fuel or material not produced	Damages to materials or persons
	Workplace accidents	Damages to materials or persons

In the table above the categories are listed for the three phases: production of plastic parts, the use phase in vehicles (listed only for LCA “total life”) and the recovery options. Typical process steps attributed to specific risk are high pressure and high temperature. Indicators for common workplace risk are workplace accidents and special transportation accidents, which involve third parties. Special risk categories have been identified as long-term stability and product risks.

Typical results are shown in the next table.

Production of plastic parts

For the production of a polypropylene (PP) bumper, elevated temperature and pressure are applied. The categories “high pressure”, “high temperature” and “accidents” have a small impact and are classified as 1. For “workplace accidents” a medium impact is estimated. This is a relative assessment in comparison with other plastics.

Transport accidents

For the phase “recovery options”, the estimation on transport risk is the same as with toxic risk. For “landfill” and “waste combustion”, the transport distance is smaller because of the large number of installations.

Handling of substances

The category “handling of flammable or explosive substances” introduces the risk of fire or explosion. Landfills have a medium impact, whereas waste combustion and syngas production have a small impact. The other processes are subjected to fire hazards too, but these are attributed to the process and not to the plastic as fuel substitute.

Disposal/long term stability- product quality

Long-term stability of waste disposal is a risk to “landfill” and to a lesser extent to “waste combustion”. For “mechanical recycling” the risk of product failure is included in the category “product quality”.

Credit for fuel or material not produced

For the category “credit for substituted material or fuel”, the risk related to the substituted material or fuel is estimated. “Landfill” has no product. For “mechanical recycling” a higher risk reduction is attributed and for the others a smaller risk reduction is estimated. When the risk potentials in this category are totalled, additional risks are shown for the fuel substituting options. Conventional fuels are estimated to have a lower specific risk because of better logistic and handling.

Workplace accidents

In the last category “workplace accidents”, the “landfill” is estimated to have an elevated medium risk because of special labour conditions related to heavy machinery and the construction of landfills. “Mechanical recycling” is labour-intensive and therefore specific risks are higher.

Table 6.4 Assessment of risk potential per weight for bumper.

		Landfill	Waste Inciner.	Cement kiln	Syngas-production	Blast furnace	Mechan. recycling
Production plastic parts	**High pressure at production**	1	1	1	1	1	1
	High temperature at production	1	1	1	1	1	1
	Accidents during Painting, etc.	0	0	0	0	0	0
	Work place accidents	2	2	2	2	2	2
	Transportation accidents	1	1	1	1	1	1
Use in vehicle	**Accidents during handling of fuels**	1	1	1	1	1	1
Recycling/ Recovery / Disposal	**Transportation/logistics accidents**	1	1	2	2	2	2
	Handling of higly flammably or explosive substances	2	1	0	1	0	0
	disposal/ longterm stability	2	1	0	0	0	0
	Product quality does not meet specifications	0	0	0	0	0	1
	Credit for not produced fuel or material	0	-1	-1	-1	-1	-2
	Workplace accidents	2	1	1	1	1	2

Both risk potential and toxic potential are semi-quantitative figures. The categories and their assessment in the different options strongly depend on expert opinion. The influence of the risk potential and the toxic potential will be discussed in the sensitivity section below.

6.2.3 Weighting of LCA Data

For our purposes, the individual data (LCA data, toxicity and risk) need to be condensed by a 2-step scheme to one indicator called “environmental burden”. The environmental burden consists of

1. ***Five categories:*** energy consumption, raw material consumption, ***emissions***, toxic potential and risk potential.
2. The ***emissions*** consists of three ***sub-categories***: ***Air emissions***, emissions to water and waste.
3. The ***air emissions*** are detailed in Global Warming Potential, Ozone Depletion Potential, Photochemical Ozone Creation Potential and Acidification Potential.

The weighting scheme is made up of two factors:

1. Societal factors give an assessment of the importance of the above categories, sub-categories and sub-sub-categories by a group of persons (valuation) with respect to the current situation in the addressed community (national, regional).
2. Normalisation of the relation between the results of the example studied and the environmental impact of a country or region (like Germany or Europe)

6.2.3.1 Societal factors: Valuation of the environmental effects by society

The scheme shows how the categories are aggregated to one indicator. The societal factors are indicated in brackets. The societal factors are derived by societal judgement, performed as opinion poll of a student group[19]. The input into the system, raw materials and energy, is assigned 50% of the total environmental burden. The remaining 50% is assigned to the inevitable output of the systems. These are emissions, toxicity (measured as toxicity potential), and risk (measured as potential risk).

The category emissions is split into air, water and waste. Half is assigned to air, 35% (app. 1/3) to water and the remaining 15% to soil, which is usually identical to waste. The air emissions are further split into four categories: global warming with a societal

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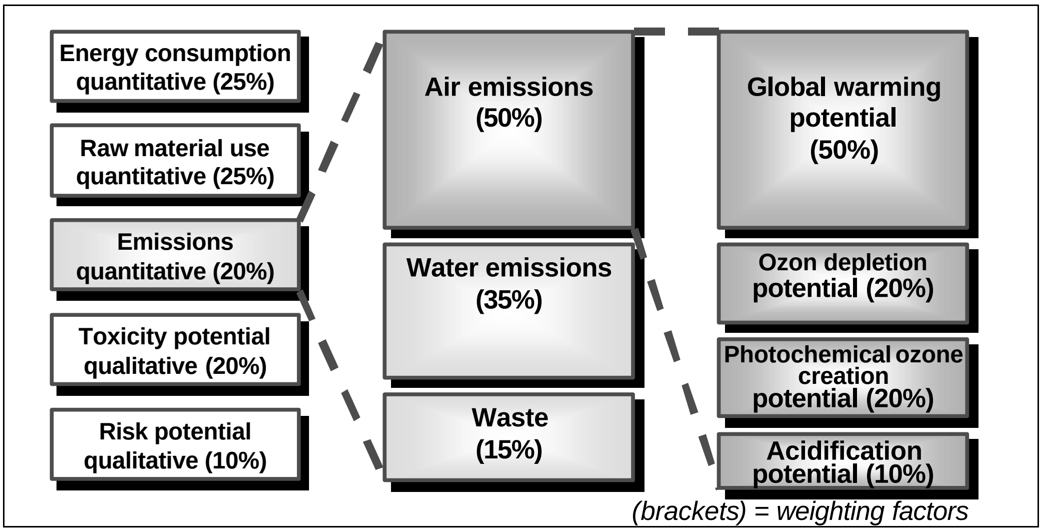
[19] See “Eco-efficiency analysis by BASF – the method”, Peter Saling et.al., BASF-AG Ludwigshafen.

factor of 50%, potential acidification with 10% and the rest for potential contribution to summer smog and ozone depletion.



(brackets) = weighting factors

Figure 6.1 Rating, weighting and evaluation scheme - evaluation of the environmental effects by society

6.2.3.2 Normalisation of the environmental effects

Normalisation is performed by division of the results by the total national impacts. The national accounts are taken from statistics[20].

$$\frac{Maximal \cdot environmental \cdot impact \cdot of \cdot options}{Total \cdot environmental \cdot impact \cdot in \cdot W. - Europe} = \mathrm{Re}levance_{Environment}$$

The maximal environmental impact is selected as a normalised result which will be processed further in the weighting scheme.

The reference for the normalisation is the environmental impact of a greater community (such as Europe). This prevents very small emissions that are immaterial to the total emission situation in Europe, for example, from being overvalued and other, larger and decisive emissions from being undervalued.

6.2.3.3 Environmental weighting scheme

The weighting scheme is arranged with the same components as the societal factors scheme (see figure above). So a comparison between the two is relatively easy. In the

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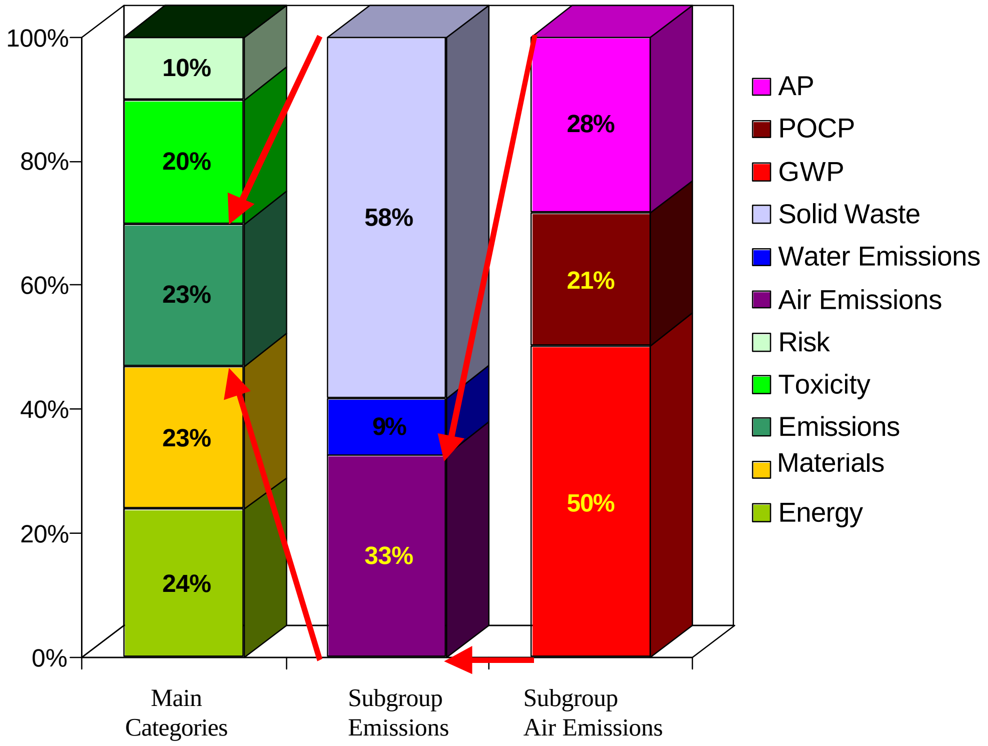
[20] The detailed inventories in the statistics are aggregated to the same level and by the same aggregation algorithm as described in chapter 5.

weighting scheme, the factors are called relevance factors and describe the influence of the different categories (see figure below).

Additional to societal factors, the normalized results contribute to the relevance factors[21]. The geometric mean of both factors (square root) gives the relevance factor which determines the influence of the single result on the overall "environmental burden" indicator[22]. The advantages of this procedure are:

1. The relevance factors always add up to 100%. Thus an easy identification of more or less important impacts is possible.
2. Relative to other impacts, important impacts (categories or sub-categories) are highlighted with respect to the societal factors. Relevance factors show a higher contribution than the preset societal factors.
3. In contrast, with respect to the societal factor, the relevance factor may be reduced if the result of a category is of minor importance

A result for bumpers is shown in the next figure.



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[21] For a detailed description of the relevance factor, please see Annex-II

[22] The factors for toxic potential and risk potential are fixed and are not subject to this procedure because a normalisation step is not possible due to a lack of data.

Figure 6.2 Weighting scheme for bumper. The relevance factors illustrate the impact of categories on the environmental burden indicator.

On the first hierarchy level the relevance of toxic potential and risk potential is fixed to 10% and 20%. Energy and material consumption get a lower relevance of 24% and 23% than their societal factors (25% each). The relevance of the emission category rises from 20% to 23%. This is mainly due to a higher relevance of the waste category which is typical for a waste related subject.

The above figures on relevance factors illustrate the influence of each category on the total result. Global warming has a 50% share of the air emissions which contribute 33% to the total emissions. Total emissions in turn make up 23% to the total indicator. So global warming has an overall impact of 3.8% in this example compared with 5% in the societal factor scheme.

In contrast, waste is given a higher relevance. In the societal factors scheme, waste contributes 3%. After weighting, the relevance of waste is 13%. Taking into account the normalized results in the considered processes, more waste is produced in comparison to the other categories with the result that waste is given a higher impact.

6.2.4 Comparison with other aggregation schemes.

The weighted aggregated environmental impact scheme used in this study has been compared with the "Eco-indicator 99" scheme[23]. Starting from the Life Cycle Inventory the single results of the inventory are multiplied by a factor which is characteristic for each single result (emission, energy consumption, raw material). The results of the multiplication are summed up and provide the total.

The factors in the "Eco-indicator 99" scheme are derived by modelling the damage to resources, eco-systems and human health and value-weighting these three categories. In this comparison the standard settings for values have been used.

The comparison between the two schemes has been performed for the bumper and the ranking of the options is shown in the table.

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[23] The "Eco-indicator 95" has also been tested. Because it has been substituted by the Eco-indicator 99 scheme the discussion will focus on the more recent one.

Table 6.5 Comparison of aggregation scheme.

Rank	Eco-indicator 99	This study
1	Mechanical Recycling	Mechanical Recycling
2	Blast furnace	Blast furnace
3	Syngas production	Syngas production Cement kiln
4	Waste combustion	
5	Cement kiln	Waste combustion
6	Landfill	Landfill

The above table illustrate that the two rankings of the options are comparable. In the Eco-indicator 99 energy consumption is the leading impact category according to the inventory results of this study. This is in accordance with the aggregation used in this study. Differences in the weighting of coal (lignite) lead to the different assessment for the cement kiln option.

The survey shows that both schemes provide comparable results.

6.3 Cost Data

Cost data should cover the same processes as the environmental data. Ideally both, cost and environmental data should be investigated inside the same system boundaries and should have the same degree of detail. For practical reasons, cost data for the options could only be obtained as gate fees. For mechanical recycling most of the data could be presented in a far more detailed degree. This is performed to display differences between plastics. It is reasonable to assume that the gate fees correspond to the system boundaries given in Section 5.

Furthermore the costs are regarded as independent of the actor who incurs them. No influence by local or national policy on the costs is taken into account.

In conjunction with the LCA, the break down of the cost parts has to be performed and the costs of the corresponding process steps have to be determined. If possible, the costs are displayed at detail level. In practice "costs" have to be replaced by prices or gate fees for complex operations. The following table gives an overview on aggregated costs and their origin:

Because of their prospective nature, many of the relevant process steps do not exist or are not realized in the configuration needed. Especially since the technology has been tested only in small-scale plants, the costs would therefore lead to misleading figures if they were to be taken for an EU-wide operation scheme. Therefore, modeling and estimations have to be employed.

For the determination of cost, the following hierarchy was set up:

1. Actual costs/prices of operators or manufactures:
   (parts, gate fees)
2. Estimation of costs for single operation units/processes by standard figures:
   (transportation, shredder)
3. Prospective cost analysis by scale modeling:
   (mechanical recycling)
4. Prospective cost estimation on the basis of expert judgment:
   (dismantling)

Table 6.6 Origin of Cost data

Phase/step	Include	Remarks	Source
Manufacturing of plastic parts	Virgin material, compounding, further processing, transport to car manufacture	OEM (Original Equipment Manufacture) list prices	Industry
Use	Gasoline	Gasoline price allocated	Literature research
ELV shredder	Shredding	Allocated	Shredder, literature
ELV dismantler	Dismantling of plastic parts		Dismantlers estimate
ELV landfill, MSWC	Waste treatment	Allocated gate fees	EU study
ELV, cement, blast furnace, Syngas-production	Waste treatment	Gate fees	Industry
ELV, mechanical recycling	Processing	Modeling	Expert estimation/industry
ELV, virgin plastic material	Benefit		Plastic industry/market survey (KI)

Unfortunately, the main costs for mechanical recycling cannot be evaluated from existing operations and thus have to be estimated. The costs of mechanical recycling are strongly influenced by the volume of recycled material. Because no general scenario on the total ELV market is performed in this study, the cost data on mechanical recycling are not subject to a sensitivity analysis[24] with respect to market penetration. The uncertainty on dismantling costs will be shown as min-max figures.

6.3.1 Transportation model

Transportation of goods is inevitable in today's economy. As far as possible a common transportation model should be applied to the processes, so comparable cost data can be estimated. For recovery and recycling transportation processes are common today. Costs and environmental impact of a specific transportation processes are not available in all cases and are subject to changes. So throughout this study a step-wise approach was used for transportation modelling:

a) If data for a distinct transportation process[25] were available (either costs or environmental impact) they were used. A check for generic validity was done.

b) If only the distance was available the following input data for the analysis were assumed:

   Transportation costs:

   If goods with relatively high specific weight are transported, the mass was used as the basis for the cost calculation of the cargo rate:

   120 DM/1000 t km or 61 Euro/1000 t km

   If goods with relatively low specific weight (foam) are transported, the volume was used as basis for the cost calculation of the cargo rate:

   20 DM/1000 m^3 km or 10.2 Euro/1000 m^3 km

6.3.2 Dismantling

Unlike the dismantling undertaken by ARN[26] for big plastic parts, large scale dismantling of medium to smaller parts has not been realized in practice. Only research

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[24] This is in agreement with the LCA. For example, the impact of electricity generation by waste combustion on the electricity mix is not discussed.

[25] All transport processes are included and made explicit in the LCA section. The costs of some transportation are included in gate fees and therefore are not transparent to the reader.

[26] Auto Recycling Netherlands BV see reference ARN 1999.

studies are known. Furthermore, the dismantling time as the main cost driver depends on the overall dismantling time. Only a few plastic parts can be removed autonomously. The dismantling of most parts relies on the advanced dismantling of others. So the costs of dismantling are strongly dependent on future developments: the dismantling strategy of the automobile industry and the quantity of dismantling.

In addition, there is no standardization of plastic parts. For example, headlamp lenses may be subject to “styling”. Reduced to their functional components, they may have a weight of only 0.3 kg but in some cars, they can weigh as much as 3 kg. On the other hand, the dismantling time is not based on the weight.

Dismantling time is the main cost driver but data are rarely available. For the selected parts, the dismantling time will be evaluated by expert judgment. Because of the high variation in dismantling time, the following approach was chosen:

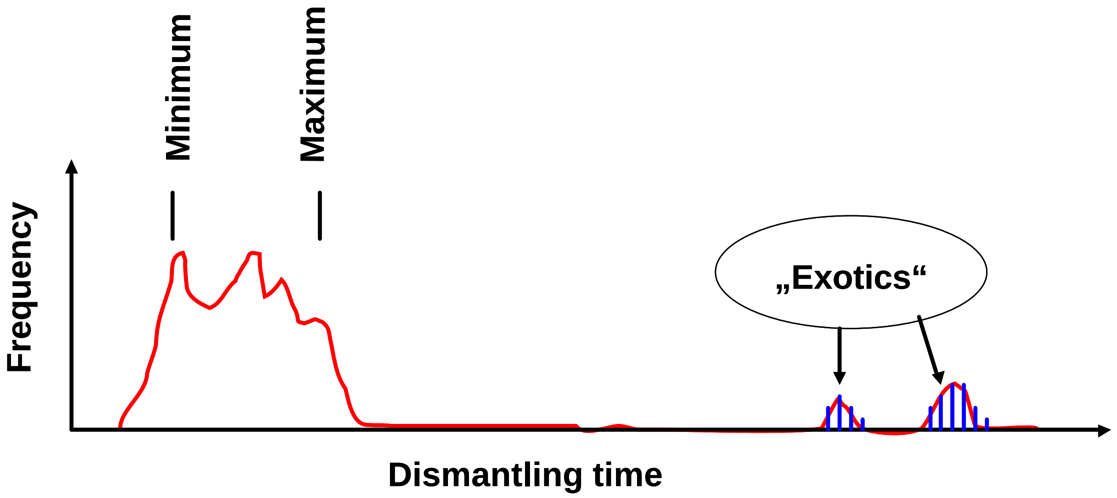

Figure 6.3 Scheme for the derivation of cost data for dismantling.

The above figure gives a sketch for a specific plastic part in ELV and its availability and corresponding dismantling time for a range of different car models. The red curve illustrates this dependence. For most ELVs a broad range may be identified and standard engineering is applied. This range is defined as typical and is indicated in the scheme with “Minimum” and Maximum”. In other ELVs the parts are situated in unusual locations or they may be of special designs. This is regarded as “exotic” and will not be covered within this study (range to the right of the “Maximum”).

This approach can be interpreted as follows: The dismantlers look for targets. The targets must be met on part level (example ARN). So the dismantlers will remove parts from ELVs where they are easily accessible and will leave “exotic” ones in place.

Dismantling costs will then be calculated from:

Dismantling costs = dismantling time x labor costs per time unit x overhead

Dismantling time represents the removal of the part itself, time needed for the use of machinery or a change of tools and the collection/sorting of parts in boxes. Dismantling time for additional parts which have to be removed first are included but no credit is given for the additional material (no allocation). The overhead includes the other operations such as further logistics, administration and management.

6.3.3 Mechanical recycling

The mechanical recycling of post-consumer engineering plastics is not realized today on a large scale. Therefore, cost data is not available according to the system boundaries in this study. In the case of bumpers[27] compounding is identified as the main cost driver. The costs of this process are highly influenced by the throughput.

Today two types of cost data are available:

1. Data for small-scale operations with a tendency of too high prices because of a rather low throughput and/or a high R&D overhead.
2. Prices for marketed recycled materials do not reflect the costs of recycling in general because the recycling material must be competitive with virgin material in order to be accepted.

Together they give the theoretical spread of costs, but none of them is realistic. This cost data has been identified as of high sensitivity for the overall assessment. Furthermore, the data come from different sources for the different parts with inconsistencies in the underlying approaches and will lead to an inherent disparity between the costs of different plastic parts/materials. Instead of presenting a broad range of guesses in a type of sensitivity analysis, a more “realistic” figure will be calculated by modeling. The model combines two parts:

a) In the first part, the amount of material available for recycling will be estimated. This amount will be derived from the specific weight of plastic parts utilized in cars and the newly licensed cars. The total amount and the number of plants calculate the throughput of the compounding plant. An expert estimated that four plants would be necessary, taking into account the need of parallel investment and logistics in Germany.

b) Taking into account the throughput, the specific compounding costs are then estimated by an expert according to normal EU market conditions taking into account material and filler.

The next figure illustrates the “scale-up” of specific costs and throughput.

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[27] In the base case bumpers are not compounded. See also Section 8, sensitivity analysis.

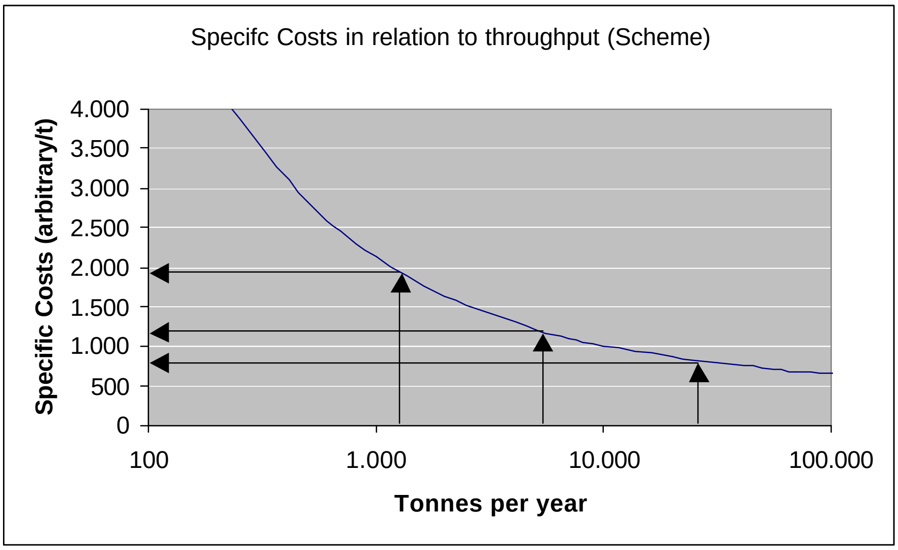

Figure 6.4 Scheme to illustrate the estimation of specific costs for mechanical recycling

In practice, the interdependence between throughput and specific cost is not so straightforward. Compounding can be done on a high capacity plant in a short time or on a low capacity plant in a longer time. Which plant is the most favorable depends on the additional cost for changing material, service and tools. The above scheme therefore displays an ideal behaviour.

The actual data are presented in the following table. Seat cushions will not be compounded.

Table 6.7 European average cost data for compounding of plastic.

Plastic part	Material	Volume for compounding	Cost
		t/a	€/kg
Bumper[1)]	PP	3000	0.25-0.3
Mirror housing	ABS	150	0.75-0.9
Headlamp lens	PC	285	0.75-0.9
Wash-liquid tank & lid	PE	219	0.75-0.9
Intake manifold	PA	800	0,76
Air duct	PP	317	0.75-0.9

[1)] Bumper will not be compounded in the base case. Data are provided for sensitivity analysis.

6.3.4 Limitations of the results

The cost data are of different quality for the different options.

Firstly, the format differs. For the option “mechanical recycling” the cost data is comparably detailed. For every process step, cost data is shown. For the other options the cost data is shown in summarized form as gate fees. Additionally, the cost data for mechanical recycling are linked to a defined throughput (compounding). Possible reduction of costs by “scale-up” is not considered.

Secondly, instead of the cost for “mechanical recycling” the gate fees are prices.

Thirdly, the detailed costs for “mechanical recycling” have a higher transparency than the gate fees. Often other costs (such as logistics) and/or revenues are included in the gate fees whereas they are shown separately in the LCA. This leads to the effect that a detailed comparison between LCA data and cost is not easily possible even if the same format of breakdown of total results is chosen.

For the options “cement kiln”, “syngas production”, “blast furnace” and “mechanical recycling” the costs or gate fees include significant revenues for fuel or material substitution. Changes in revenues result in even higher changes of the total sum.

Beyond this, estimation of the variation in costs caused by changing market prices (oil price) is extremely different. For “landfill” and “MSWC” no such impacts can be identified. For “syngas production”, “cement kiln” and “blast furnace” the price of coal or heavy fuel oil has a significant impact. It can be estimated that 50% of the gate fees result from internally calculated revenues for fuel substitution. But over the last decade the coal and heavy fuel oil price has been relatively stable. By contrast, the changes in the price of virgin plastic have been relatively high. Future developments in prices of virgin plastic may have a major impact on the overall costs for recycling.

6.3.5 Cost input data and result

In the next table the input data for cost are shown. Cost data for production and use phase are included for completeness.

Costs are determined for every step. Wherever possible, a common calculation platform is used to calculate the cost per part. The various costs are shown in the column “input data”. The cost per part can be calculated from this specific cost and the corresponding weight; transport distance or working hours are listed in the LCA input sheets.

The cost balance is shown in the following table. “Landfill” is the cheapest options with total costs of 26 cents per part. Please note that the gate fee for landfill listed here is for a high-standard landfill and the actual prices are lower. For “waste combustion” and the other processes which substitute fuel, the cost are in a medium range from 35 cents/part to 68 cents/part, where processing of plastic parts is the main cost driver. For mechanical recycling two cost figures are shown, one with lower and one with higher expenditure on dismantling. In both, dismantling is the main cost driver responsible for approximatley 50% of the cost. The other main cost is processing/compounding. On the other hand, mechanical recycling can create significant revenues. Unlike the other options, where the cost calculation is relatively straightforward, the cost calculation of mechanical recycling consists of three main costs.

Table 6.8 Cost input data for base case “bumper” (no compounding).

Process	**Costs (€)**				**Source**
	input data		**per part**		
Production			17,50	Euro	Basell 2001 a
Use					
Additional fuel consumption	1,12	Euro/l	18,54	Euro	Estimation
Mechanical recycling - manual dismantling of the lens.					
Transportation	0,003	Euro/t	0,010	Euro	BASF 1998
Dismantling bumper min	30,7	Euro/h	0,750	Euro	VKE/FAT
Dismantling bumper max	30,7	Euro/h	1,202	Euro	VKE/FAT
Processing	0,39	Euro/kg	1,24	Euro	Grannex 2002
Compounding	0,0	Euro/kg	0,00	Euro	0
Transportation	0,02	Euro/kg	0,08	Euro	BASF 1998
Recycled granules					
Marketing	0%	of sales prize	0,00	Euro	Grannex 2002
Revenues recycled material	0,46	Euro/kg	-1,27	Euro	Grannex 2002
Residues (to waste incineration)	103,00	Euro/t	0,04	Euro	Öko-Institut
Landfill					
Transportation	0,003	Euro/t	0,010	Euro	BASF 1998
Shredder	6,817	Euro/t	0,021	Euro	R-plus 2001
Transportation			0,01	Euro	BASF 1998
Landfill	70,4	Euro/t	0,22	Euro	Öko-Institut
Energy recovery (cement kiln);					
Transportation	0,003	Euro/kg	0,010	Euro	BASF 1998
Shredder (Electricity)	6,817	Euro/t	0,020	Euro	R-plus 2001
Transportation	0,006	Euro/kg	0,019	Euro	BASF 1998
Processing	102,26	Euro/t	0,32	Euro	BASF 1998
Gatefee recycled material	0,026	Euro/kg	0,076	Euro	Zement 2001
Residues (to waste incineration)	70,435	Euro/t	0,011	Euro	Öko-Institut

Table 6.9 continued

Raw material recycling (Syngas-production)					
Transportation	0,003	Euro/kg	0,010	Euro	BASF 1998
Shredder (Electricity)	6,817	Euro/t	0,020	Euro	R-plus 2001
Transportation	0,006	Euro/kg	0,02	Euro	BASF 1998
Processing; electricity	102,26	Euro/t	0,32	Euro	0
Gatefee recycled material	0,08	Euro/kg	0,23	Euro	R-plus 2001
Waste incineration (municipal)	103,00	Euro/t	0,02	Euro	Öko-Institut
Municipal waste incineration					
Transportation	0,003	Euro/t	0,010	Euro	BASF 1998
Shredder	6,817	Euro/t	0,020	Euro	R-plus 2001
Mun. Waste inc. -Costs	103	Euro/t	0,32	Euro	Öko-Institut
Raw material recycling (blast furnace)					
Transportation	0,003	Euro/kg	0,010	Euro	BASF 1998
Shredder (Electricity)	6,817	Euro/t	0,019	Euro	R-plus 2001
Transportation	0,006	Euro/kg	0,019	Euro	BASF 1998
Processing; electricity	102,3	Euro/t	0,3	Euro	Öko-Institut
Transportation			0,12	Euro	BASF 1998
Gatefee recycled material	0,06	Euro/kg	0,16	Euro	(1)
Waste incineration (municipal)	103,00	Euro/t	0,03	Euro	Öko-Institut

(1) estimation by Oeko-Institut, see Section 5.6.1.

All three costs, dismantling, compounding and revenues, show inherent uncertainties which may influence the total cost significantly. The cost for dismantling is only an estimate, based on actual vehicle design. This may change with time. The compounding cost relies strictly on the assumption concerning the volume of recycled material. Introduction of new materials or a new policy from car manufactures may change this volume. The revenues on recycled material are also subject to change. Firstly, the price for virgin material is changing with oil price. This influence is not as significant for PC as for PP, but prices can vary by as much as 50%. Secondly, the market for recycled material itself may change. Today, recycled plastics have only a small share of the market for engineering plastics.

Table 6.10 Results of cost calculation for scenario “bumper”(Euro/part)

	Landfill	Waste Incin.	Cement Kiln	Syngas-production	Blast Furnace	Min - Mechan. Recycling	Max - Mechan. Recycling
Transportation	0.016	0.010	0.029	0.029	0.144	0.087	0.087
Shredder	0.021	0.020	0.020	0.020	0.019	0.000	0.000
Processing /Compounding	0.000	0.000	0.321	0.321	0.321	1.236	1.236
Dismantling	0.000	0.000	0.000	0.000	0.000	0.750	1.202
Gate fee	0.221	0.323	0.076	0.229	0.159	0.000	0.000
Revenues	0.000	0.000	0.000	0.000	0.000	-1.272	-1.272
Others	0.000	0.000	0.011	0.016	0.033	0.039	0.039
Total	**0.259**	**0.353**	**0.458**	**0.615**	**0.676**	**0.840**	**1.292**

6.4 Economic weighting factors and total weighting between ecology and economy

6.4.1 Cost Relevance

The total costs of an option can be related to the total sales of the manufacturing industry or alternatively the GDP. This procedure follows the calculation of the relevance factors[28] for total environmental impact and will give a relevance factor for the cost element, the cost relevance factor “Relevance$_{\text{costs}}$”. This factor reflects the extent to which the options studied contribute for example to the gross domestic product of a country. In absolute terms, the value is very small, but it can be used for comparison.

$$\frac{Maximal\cdot \mathrm{cost}\cdot of\ \cdot options}{Sales\cdot of\ \cdot total\cdot manufacturing\cdot industry\cdot in\cdot W.-Europe} = \mathrm{Re}\,levance_{Costs}$$

For most recovery options, gate fees substitute the costs. Gate fees are a combination of costs and credits. For example, in cement kilns the costs represent additional investment, cost for extension of permits and costs which cover the extra costs for handling and management of plastic fuels. Credits for substituted conventional fuels reduce these expenditures.

6.4.2 Weighting of ecology and economy

Both factors, the Relevance$_{\text{costs}}$ and the Relevance$_{\text{environment}}$ can now be used to link the results of the cost component and the environmental component. The ratio of both gives the “weight” of the environmental versus the cost impact:

$$\frac{\left(\dfrac{Max\ environ.\ impact}{total\ environ.\ impact}\right)}{\left(\dfrac{Max\ Cost}{total\ Cost\ (GDP)}\right)} = \frac{\mathrm{Re}\,levance_{Environment}}{\mathrm{Re}\,levance_{Cost}} = \frac{E}{C}$$

The link between environmental burden and cost are introduced by the E/C ratio. An E/C ratio higher then 1 iondicates that the processes are causing a higher environmental burden than average processes with respect to costs. The environmental indicator has a higher “weight” than the cost indicator. An E/C ratio lower than 1 is indicates that the

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[28] Because cost are not subject to societal factors, the relevance factor for cost is identical with normalisation.

processes exhibit a lower environmental burden with respect to costs. The cost indicator has a higher “weight”.

The calculated indicator (IND_{Cost} and $IND_{Environ}$) have now to be translated to the portfolio where one unit on the environmental axis should refer to a fraction of the total environmental inventory of a country and one unit on the cost axis should refer to the same fraction (of GDP for example) of the same country. The new adjusted environmental and cost indicators ($IND_{Cost,Adj}$ and $IND_{Environ,Adj}$) are derived from the old ones and the E/C ratio:

$$\left(\frac{IND_{Environ,Adj}}{IND_{Environ}}\right)\times\left(\frac{IND_{Cost}}{IND_{Cost,Adj}}\right)=\frac{E}{C}$$

If the units on both axes in the portfolio have the same “weight”, the following secondary condition is needed.

$$\frac{IND_{Environ,Adj}}{IND_{Cost,Adj}}=1$$

If the slope between one unit on both axes is 1 (= 45^0), the diagonal represents the slope between the total environmental burden and the total cost of the country in question. In other words, the diagonal represents the eco-efficiency of the country.

The E/C ratio is now used to adjust the results of the environmental burden indicator and cost indicator. The indicators are further processed to obtain a centered portfolio[29],; the average of all options is 1.

This complex procedure is chosen to identify the ***differences*** of the considered alternatives in terms of the eco-efficiency of a country (state, region). Whether the alternatives themselves are eco-efficient with respect of the total system is not a subject of the study. The considered alternatives provide a service or product to the client described in the functional unit.

6.5 Portfolio diagram

The data from the eco-efficiency analysis are presented in a portfolio diagram. The cost is on the x-axis and the environmental burden on the y-axis. The average of all options

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[29] More details about the algorithm are presented in Annex-II.

is set to a value of 1, which is displayed as the centre of the portfolio. For both axes the same maximum values and length are displayed, so that the portfolio is symmetrical. Note that the portfolios for the different plastic parts cannot be compared, because the relative values on the axes and the average may have changed.

As shown in the next diagram, the options are presented as coloured balls in the graph. The best, most eco-efficient option would be placed on the top right-hand side of the diagram (low cost and environmentally friendly). The area in this quadrant is coloured green. The worst is in the lower left-hand quadrant which is shown in red (high environmental burden and expensive). An assessment of two options in which one is located in the green area and one in the red area would be is easy to make. In practice, the differences between two options are usually not so clear. To identify the most eco-efficient option, one has to consider which option has the best cost-environment ratio. Or in other terms, how much additional cost would be incurred to pay for a reduction in the environmental burden and is this added cost reasonable?

A reasonable cost-environment ratio is indicated by the E/C ratio (see the section above). One unit of cost buys one unit of environmental burden under the same conditions that were introduced by the Relevance factor, namely the same condition as at the national or regional level. So if the difference between two options is that one unit of additional cost buys one unit less of environmental burden, they are assessed equally. There is no incentive to incur (or not to incur) additional costs, as the cost-environment ratio is the same as on national level. Both options exhibit the same eco-efficiency.

On a more general level, eco-efficiency in our portfolio is defined as

$$\frac{1}{eco-efficiency} = [relative \quad environmental \quad burden] + [relative \quad cost]$$

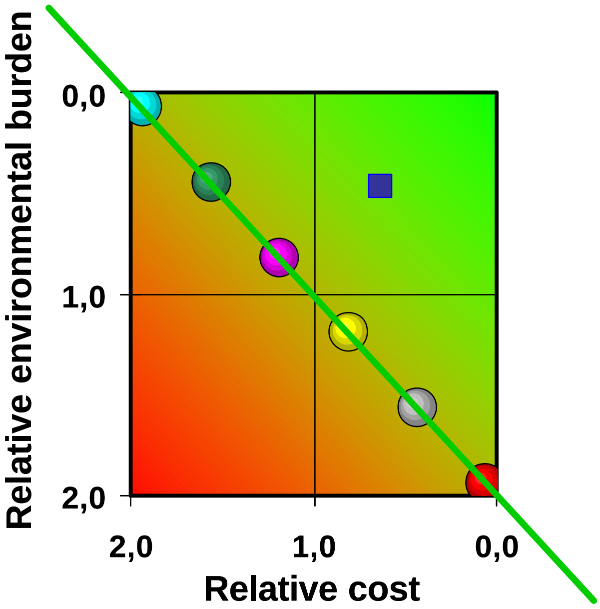

Figure 6.5 Scheme of the portfolio diagram

Options with the same “eco-efficiency” are therefore placed on a 45^0 slope if both axes in the portfolio have the same scale. One 45^0 slope, passing through the centre, is the diagonal. It is shown in the portfolio for practical reasons to allow an easier assessment by the reader.

Compared with the yellow ball in the figure above, the pink one is more environmentally friendly but also more costly. On the basis of our underlying system, no gain in eco-efficiency is realized if the option pink is chosen instead of yellow. On the other hand, the grey ball is less costly but less environmental friendly but still on the same eco-efficiency level. No gain in eco-efficiency is achieved by choosing grey instead of yellow. The most eco-efficient option in this portfolio is represented by the dark-blue square. The green line of eco-efficiency has to be moved to the top right-hand corner in order to accommodate the deep-blue square. This option is more favourable than all the others in terms of eco-efficiency.

On the macro level, the important point of this assessment as a selection criterion is: If the most eco-efficient options are selected within this scheme, the total regional or national system becomes more eco-efficient. Because the objectives are well-defined services or products, the service or product output of the economy stays the same.

If many services or products are selected under this procedure, and assuming that the options are equally distributed over the portfolio, the sum of all services or products will exhibit:

- A more eco-efficient system
- Lower cost with an environmental burden equal to pre-procedure condition
- Less environmental burden without additional cost
- Or a combination of lower cost and less environmental burden than the pre-procedure condition.

So even an option selected on the micro level which has higher costs but generates a lower environmental burden would be acceptable on a macro level because other processes will compensate the higher costs.

7 Eco-efficiency analysis - results

The results are shown first for each part in a portfolio diagram. The detailed results for each plastic part are presented in the Annex. The option “mechanical recycling” is presented in two alternatives. As introduced in Section 6.4 “Cost”, the two alternatives represent high and low dismantling times and hence costs.

7.1 Headlamp lens

Headlamp lenses are medium sized parts made from a relatively high priced plastic. The lenses are embedded in the headlights, so dismantling efforts are high. The high costs are represented in the portfolio. Both of the mechanical recycling options are over on the left hand side. On the other hand, polycarbonate has a long production chain and thus the environmental burden of production is high. For these reasons the recycling of the headlamp lens shows significant environmental benefits. However, in both of the mechanical recycling options the environmental benefits cannot compensate for the high costs. All of the other options have a better eco-efficiency profile. Drawing a diagonal in the portfolio, both mechanical recycling options are on the left side of the diagonal, indicating a significantly lower eco-efficiency than all other options.

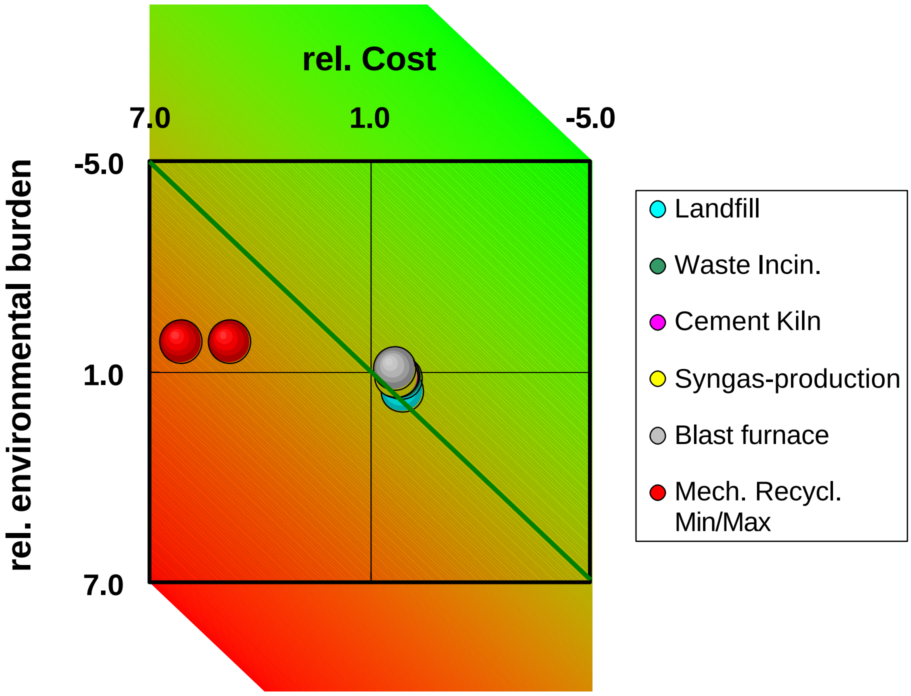

Figure 7.1 Eco-efficiency portfolio of headlamp lens (polycarbonate)

The next figure focuses on the other options which are compressed together in figure 7.1 because of the scale demanded by the high costs of mechanical recycling.

"Landfill" is the option with lowest cost but the worst environmental performance. However, the lower cost cannot fully compensate for the poor environmental performance. The "landfill" option is on the left side of the diagonal, indicating clearly a poor eco-efficiency profile. The other options are relatively close together. "Waste combustion", "Cement kiln" and "Syngas production" show an overlap. The general pattern of these three options suggests a better environmental performance than landfill but with higher costs. The "blast furnace" has a lower environmental burden and only small additional cost. This option indicates the best eco-efficiency of all options studied.

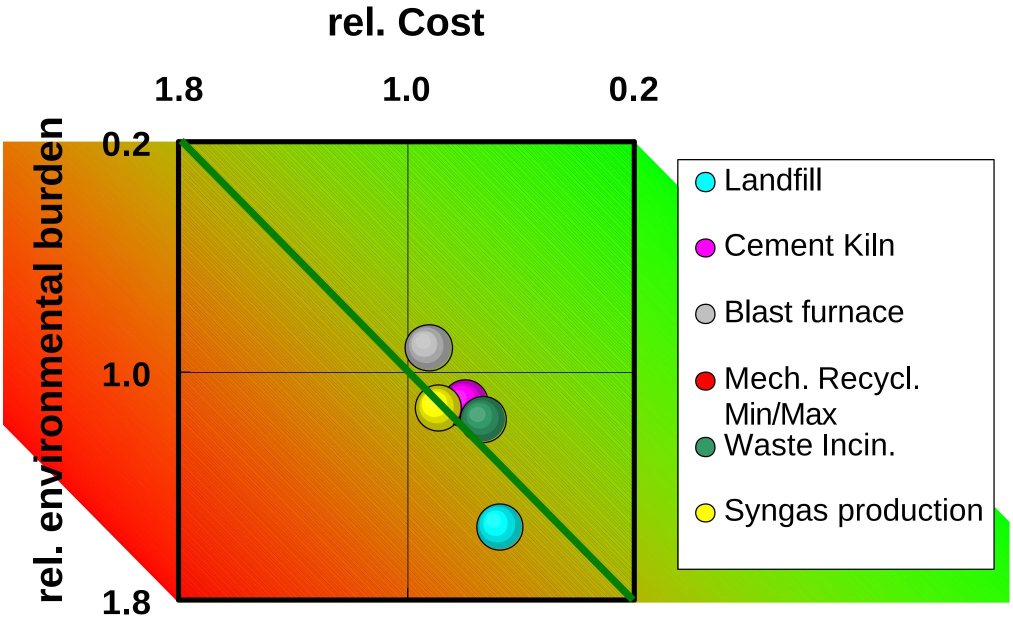

Figure 7.2 Eco-efficiency portfolio of headlamp lens (polycarbonate), selected options, zoom of Figure 7.1.

Further analysis shows that the better eco-efficiency performance of the "blast furnace" option is mainly due to the effect of fuel oil substitution. In contrast to other fuels, fuel oil has a higher value in the category "resource depletion" and credits are given for fuel oil in the categories "toxic potential" and "risk potential". A blast furnace running on fuel oil was chosen because plastic recovery is realized in this type of blast furnace. Nevertheless fuel oil has a low market share in the blast furnace process at a European level. If the recovery of plastics in blast furnaces increases in the future, coal will be substituted. As a consequence, the eco-efficiency of the blast furnace process will get closer to those of cement kiln and syngas production.

In total, all option are assessed to score equivalent except landfill and mechanical recycling.

7.2 Bumper

The bumper is the heaviest plastic part selected in this study. Bumpers are relatively easy to dismantle. In this study only bumpers made of polypropylene (PP) are considered. PP is a relatively low priced plastic.

From the beginning of this study, bumpers have been estimated to be one of the most efficient parts to recycle. This initial assessment was confirmed by the eco-efficiency analysis. The dismantling time is very short and the differences between the bumpers in different cars are relatively small.

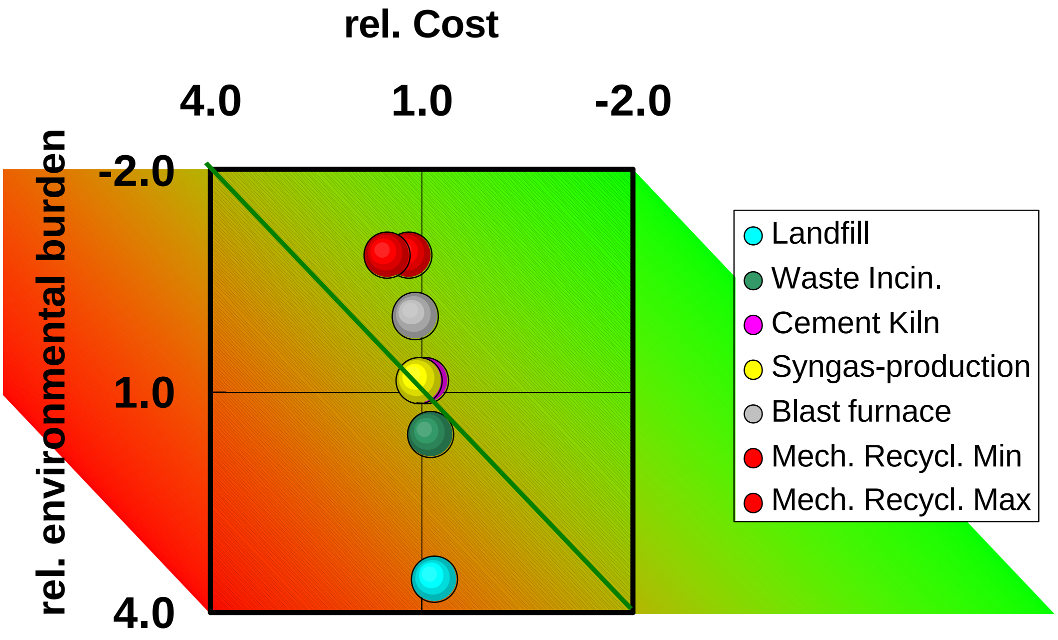

Figure 7.3 Eco-efficiency portfolio of bumper (polypropylene).

On the other hand the bumpers are made of polypropylene (PP) which has a high heat value and thus would be a preferred material for fuel substitution.

The portfolio diagram depicts a very clear picture of the options. “Landfill” has a very poor ecological profile with lowest cost. “Waste combustion”, “cement kiln”, “syngas production” and “blast furnace” all utilise the heat value. The eco-efficiency analysis shows them in a line but with a steep slope. The differences in cost are smaller than the changes in environmental burden. Drawing a diagonal through the diagram, “waste combustion” has the poorest eco-efficiency performance of these four options. “Cement kiln” and “syngas production” have a significant overlap. “Blast furnace” has the best eco-efficiency profile of the four.

The “mechanical recycling - Min” can be seen as the option with the highest eco-efficiency. The environmental burden is lowest and the cost is the highest of all options considered (except the Max-version). In the eco-efficiency assessment this option has the best profile. Despite the existence of recycling plants for bumpers, the market for recycled PP is limited today.

Both options for “mechanical recycling” are the most eco-efficient options followed by the “blast furnace”, then by the “cement kiln” and “syngas production” options.

Looking at the main parameters influencing these eco-efficiency profiles, the “blast furnace” may have the tendency for a higher environmental burden because the plastic substitutes fuel oil (see discussion above). The environmental profile of “mechanical recycling” is linked to the substitution factor (see discussion below).

For the fuel substitution or energy recovery processes, the costs are quite stable because the price of fuel or energy represents only a fraction of the gate fees. In the case of “mechanical recycling”, the prices are dependent on the price of virgin material, which in turn is linked to oil prices. Changes in the price[30] of virgin material by a factor of two have been observed in the past.

The option “mechanical recycling” has the potential to show the best eco-efficiency profile. Taking the influencing parameters into account, the assessment looks quite stable. The only factor which may have a severe impact is the substitution factor (see sensitivity analysis).

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[30] As PP is a plastic with a high production volume, future decreases in price because of lower unit costs will be limited. However, nobody can forecast drastic changes in oil price.

7.3 Seat Cushions

Seat Cushions (without head rest and back rest) are made of polyurethane foam (PU or PUR). PU is a relatively high priced plastic with a heat value comparable to coal. Therefore mechanical recycling could be an interesting alternative. For “mechanical recycling” the dismantled material is processed (removing impurities) and then fed to an existing recycling pathway. The recycled material is used as a carpet underlay in USA. The market for material in this pathway is currently limited.

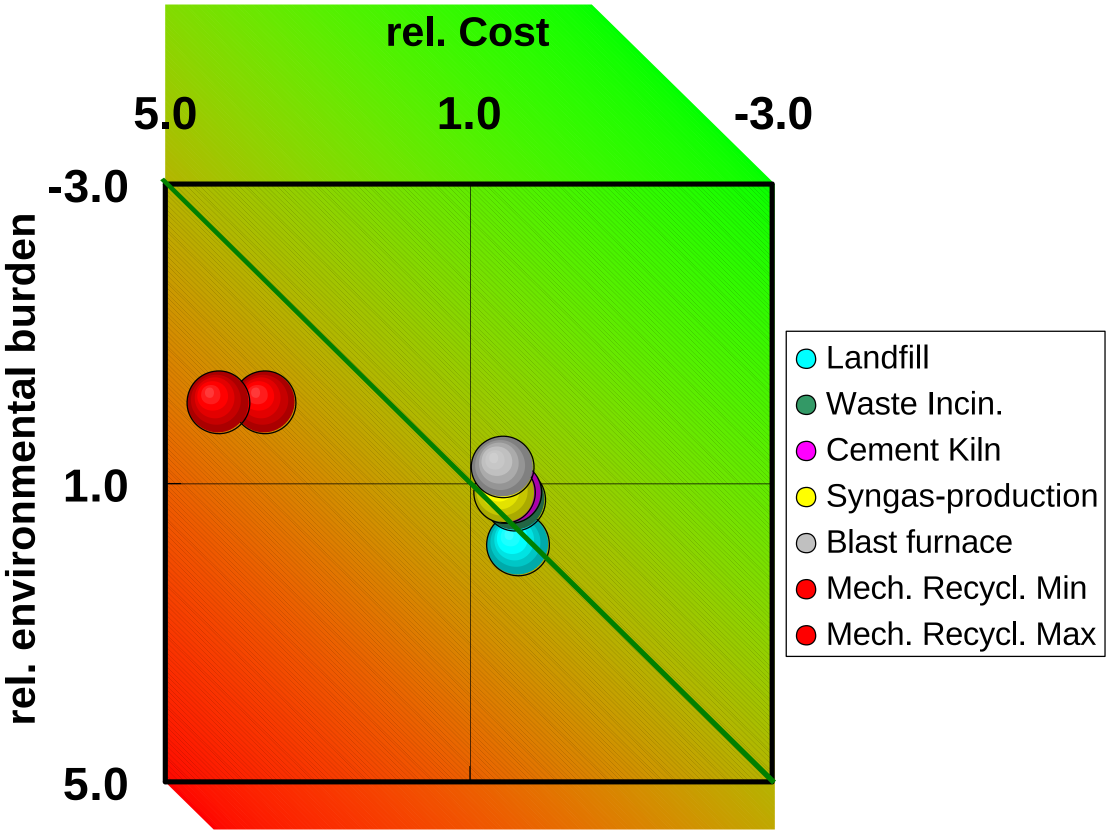

Figure 7.4 Eco-efficiency portfolio of seat cushions (polyurethane).

The portfolio diagram shows a clear picture. From an environmental point of view the recycling options are the best. However, the costs are very high. From the eco-efficiency point of view “mechanical recycling” is the least attractive. The processing of the dismantled material causes high costs. The other options show a better performance with “blast furnace” having the highest rank, followed by “syngas production”, “cement kiln”, “waste combustion” and “landfill”.

7.4 Intake manifold

The plastic air intake manifold is a high-tech part normally used in diesel-fuelled engines. It is made of PA 6 or PA 66 with a glass-fibre filler (app. 30%). The types of intake manifolds differ significantly in weight and an average weight of app. 0.7 kg has been chosen in this study. PA is a medium/high-priced plastic with a relatively low heat value.

Located in the engine compartment, there can be large differences in accessibility for removal of the intake manifold. This is reflected in the large divergence in the costs of "mechanical recycling". In the portfolio diagram below, the large range between the Min- and Max-options in "mechanical recycling" can be clearly seen.

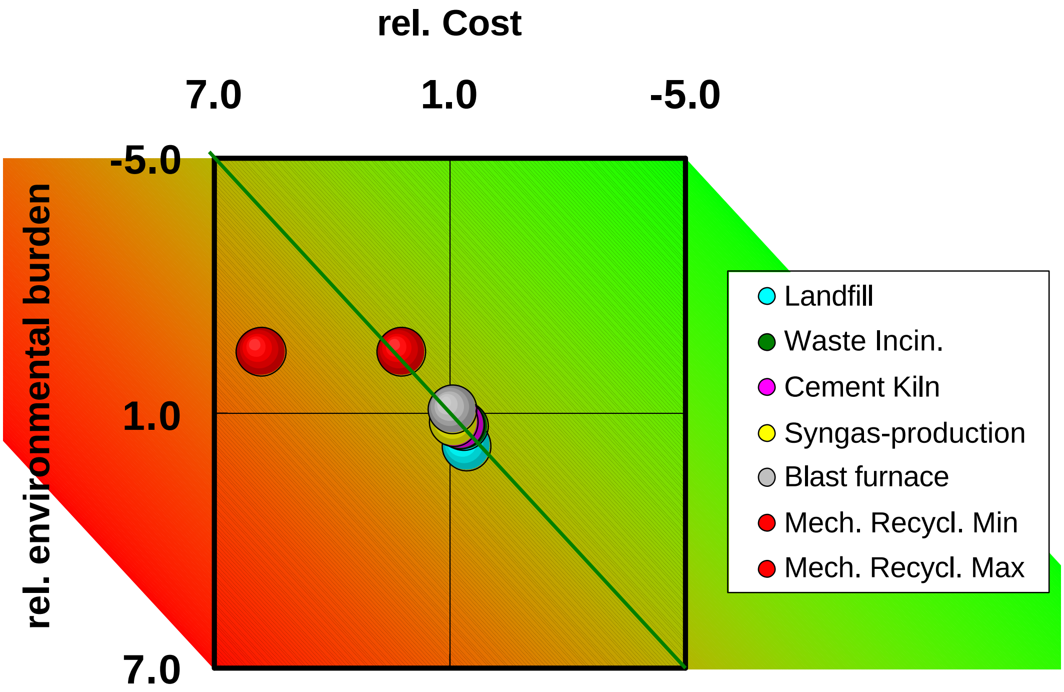

Figure 7.5 Eco-efficiency portfolio of intake manifold (polyamide).

The other options are in line with the results found for other parts. The ranking for these options is the same as in the other figures with "blast furnace" ranking high and "landfill" ranking low.

Drawing a diagonal in the portfolio diagram, the diagonal runs through the fuel or feedstock substition options and the "mechanical recycling-Min" option. These options can be regarded as equivalent in terms of eco-efficiency. The "mechanical recycling Max" is clearly on the left hand side and thus shows the poorest eco-efficiency profile. The message from this portfolio analysis is quite clear: the decision whether mechanical recycling should be the favourite option depends on the dismantling time and weight of the intake manifold. Information whether the Min or the Max alternative is the more likely is missing and only the arithmetic average can be used. Taking this average it would show a worse eco-efficiency than the energy or feedstock recovery options.

7.5 Air duct

The air duct is located in the interior of the car and delivers fresh air to the passenger compartment. Because the air duct is hidden behind frames or the dashboard, the dismantling always involves a pre-dismantling of other parts. The air duct system has many parts. In this study the most likely situation of an air duct behind the dashboard has been chosen. The weight of the air duct is approximately 0.95 kg. It is made of 80% polypropylene (PP) and 20% filler (talc). For dismantling, the dashboard has to be removed first. This cost is included.

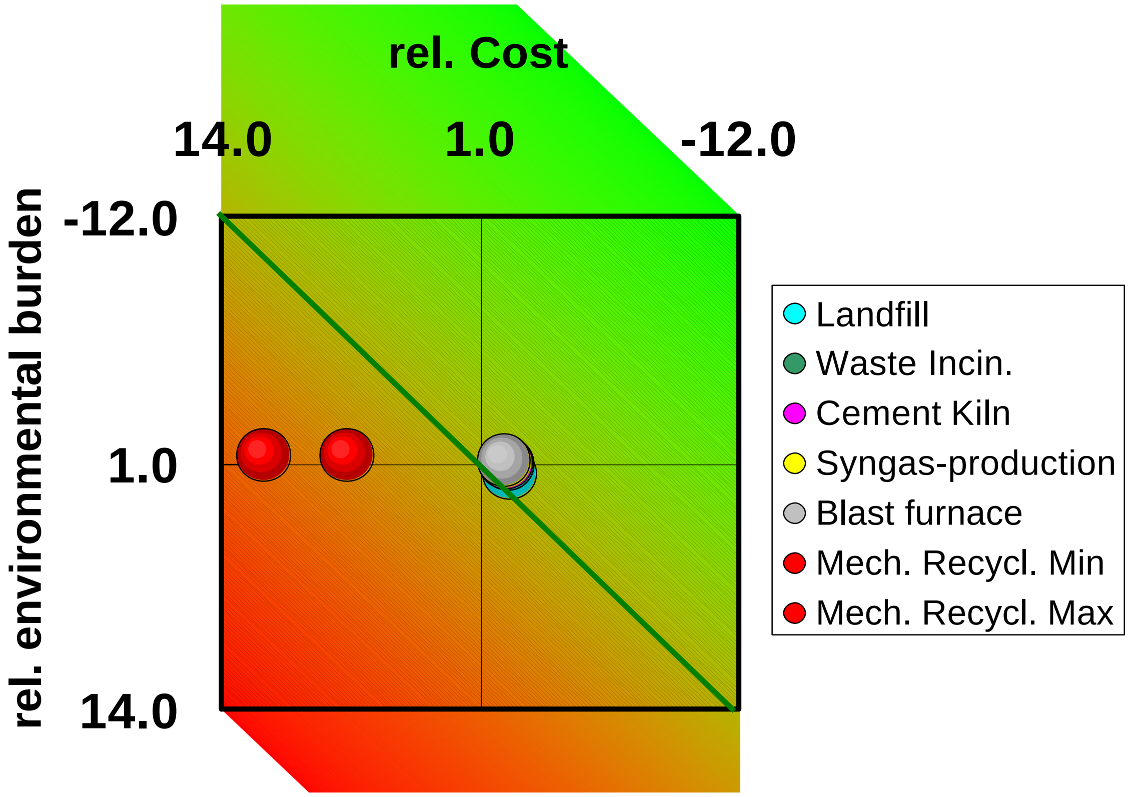

Figure 7.6 Portfolio diagram of an air duct (polypropylene)

The figure illustrates the eco-efficiency of the air duct recovery options. The environmental burdens[31] of the options show a clear preference for “mechanical recycling” followed by “blast furnace”, “syngas production”, “cement kiln” and “waste combustion”. “Landfill” has the highest environmental burden. Relative costs run in the opposite direction.

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[31] Note that the figure is very condensed in comparison to the other eco-efficiency diagrams.

The eco-efficiency analysis of the options indicates that "mechanical recycling Min and Max" are the poorest alternatives in comparison to the fuel substituting options. The fuel substituting processes are quite close with "blast furnace" ranking relatively the highest and "waste combustion" ranking lowest. The "landfill" option is significantly worse than all of these.

A first order estimation of the "mechanical recycling" option show that the allocation of costs involved in the first dismantling step plays an important role. If this dismantling effort is only attributed to the air duct, which is the methodology applied in the present calculation, the cost are far higher and both recycling options have to be regarded as having a bad eco-efficiency.

7.6 Mirror housing

The external mirror consists of the mirror, mirror housing, mirror foot, metal and electrical equipment. For dismantling, the mirror in total is removed and then the mirror housing is dismantled in a second step. The total dismantling time is included. Large differences can be observed in dismantling time.

As a typical mirror housing a 0.27 kg part is chosen. The mirror housing is made of ABS, a low/medium priced plastic with a high heat value.

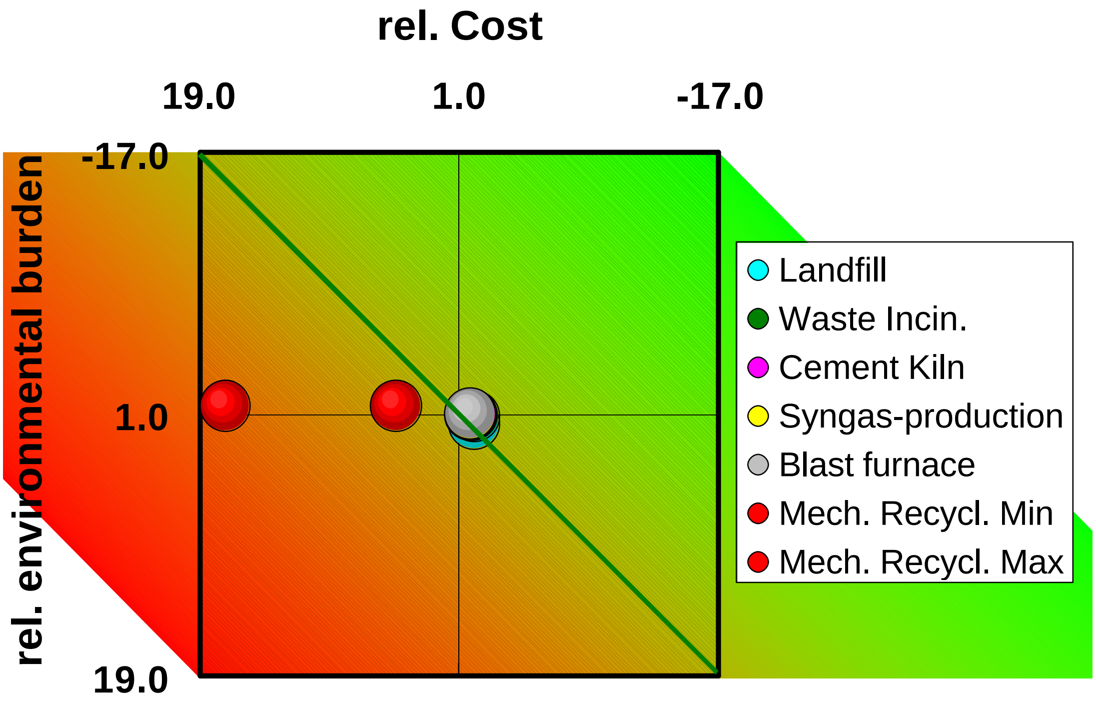

Figure 7.7 Portfolio diagram of the mirror housing (ABS).

Recycling of the mirror housing is attractive from the environmental point of view. But mechanical recycling could be very expensive as in the Max-alternative and the lower environmental burden cannot compensate the extra costs. Drawing a diagonal, the "mechanical recycling-Min" alternative shows a poor eco-efficiency in comparison to the non-recycling options. The "mechanical recycling-Max" option is far on the left hand side, indicating a very poor eco-efficiency profile. For the other options, the same ranking in eco-efficiency is noted. "Blast furnace" is ranking highest; "landfill" is ranking lowest. The results show clearly that mechanical recycling is only a favourable option if dismantling time and therefore costs are low.

7.7 Wash-liquid tank and lid

The wash-liquid tank, together with the lid, is located in the engine compartment. The tank and lid assembly is easy to dismantle. A separation between tank and lid is not reasonable. Therefore the tank and lid are aggregated and presented together. In this study it was assumed that both are made of polyethylene (PE), and these plastic parts are analysed together.

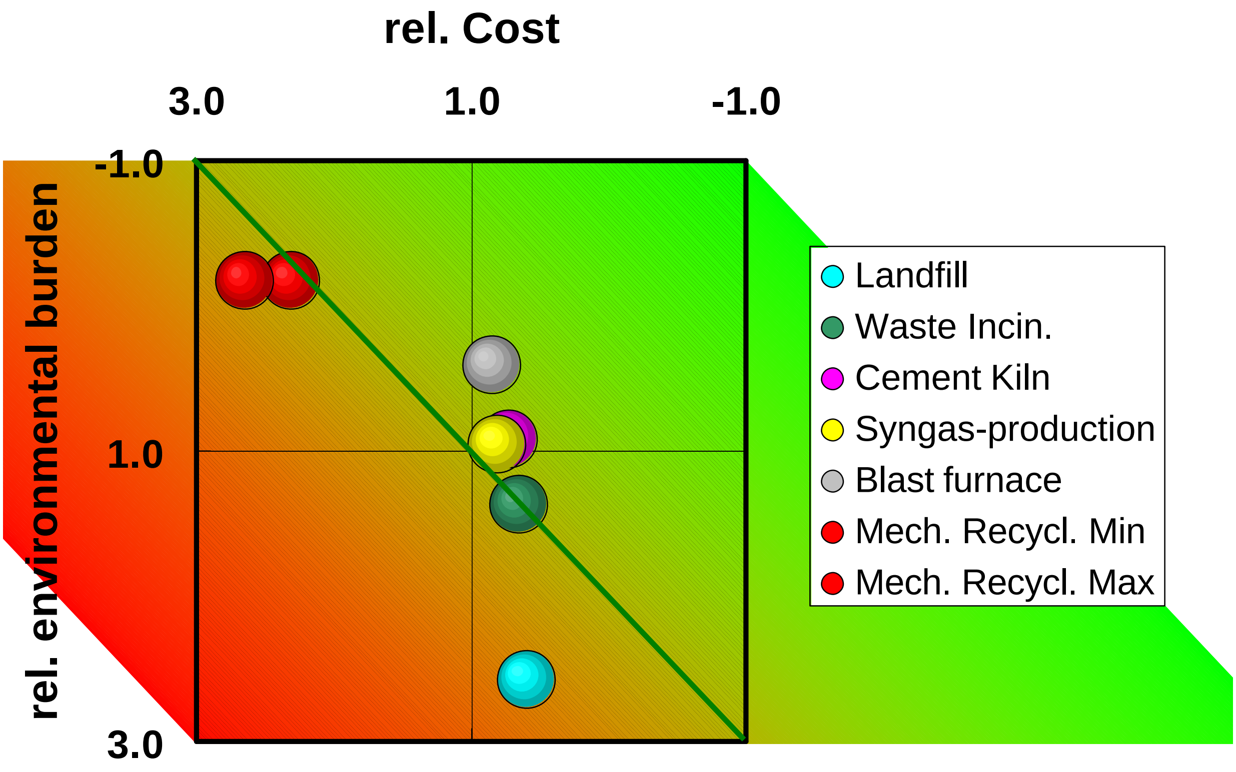

Figure 7.8 Portfolio diagram of the wash-liquid tank and lid (PE).

The dismantling times for Min and Max alternative are close together and enable a very clear picture in the eco-efficiency analysis. Both have an eco-efficiency comparable to “waste combustion” and a better profile than “landfill”. “Blast furnace”, “cement kiln” and “syngas production” score better in terms of eco-efficiency than “mechanical recycling” or “waste combustion”.

8 Discussion and Sensitivity Analysis on Parameters of Mechanical Recycling

An eco-efficiency analysis was performed for seven automotive parts. The current standard disposal route “landfill” shows the poorest performance for all of them. Municipal waste combustion (MSWC) is assessed significantly better but there is still a gap between this and the three other feedstock or energy recovery options: “blast furnace” “cement kiln” and “syngas production”. With “landfill” as a starting point and moving to the energy recovery options, the gains in environmental performance are higher then the increase in costs. In the portfolios this trend is indicated in the steep rise from “landfill” to the others.

For “mechanical recycling”, the analysis shows that the performance depends strongly on the plastic parts considered. All “mechanical recycling” options[32] show a better environmental performance than the other options but are associated with a sharp increase in costs. In terms of eco-efficiency, only bumpers shows a better eco-efficiency for mechanical recycling than the corresponding best other option. Under special conditions (minimum costs), intake manifold and wash-liquid tank are in the same eco-efficiency region as the average energy recovery processes.

For “mechanical recycling”, the parameter with the biggest influence is cost, especially the cost of dismantling. Other costs, mainly processing, are also important but do not vary drastically between the plastic parts. The dismantling costs are influenced by the weight and accessibility of the part. Big parts like bumpers perform well whereas seat cushions show a poor eco-efficiency due to costly dismantling and processing. The same results can be observed for medium parts. The intake manifold shows a far better eco-efficiency than the air duct. The smaller parts exhibit poor eco-efficiency. An exception is the wash-liquid tank which is easily accessible.

8.1 Mechanical Recycling

Mechanical recycling of plastics is always accompanied by a degradation in mechanical strength. Simply using more plastic material can compensate for this degradation. But this approach would lead to increased weight of automobiles, which would cancel out the weight reduction benefit of the initial substitution of steel by plastic in automobiles. Nevertheless, there are plastic applications in cars where the mechanical strength is not the governing principle and recycled plastic material can be used without increasing weight. Ford or GM/Opel claim to utilize as much as 20% recycled plastic material[33] in certain cars. The key parameter which describes the effect of substituting virgin plastic by recycling plastic is the substitution factor. The substitution factor is the ratio of

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[32] In the base case with a substitution ratio of 1.

[33] The recycling plastic material is not post- consumer or end-of-life-vehicle plastic but primary waste.

virgin to recycled material for the same application. A substitution factor of 1 indicates that recycled material can substitute virgin plastic without increased weight of the product. If more recycling material is needed to compensate physical properties then the substitution factor is lower than 1. The substitution factor is an important factor and will be discussed in detail in this sensitivity section.

For recycled material from ELVs five classifications are possible:

Case 1 "Closed-loop automotive" recycling. The recycled material goes to the same application in the car and substitutes virgin material at the same weight. The substitution factor is 1.

Case 2 "Open-loop automotive" recycling. The recycled material from the ELV goes to an automotive application where a recycled material with lower physical properties can substitute virgin material at the same weight. The substitution factor is 1.

Case 3 "Closed-loop" or "open-loop" automotive recycling with a substitution factor lower than 1. In this case the recycled material needs more weight than virgin material to compensate its physical properties.

Case 4 "Open-loop" non-automotive recycling with a substitution factor of 1.

Case 5 "Open-loop" non-automotive recycling with a substitution factor lower than 1. Plastic recycled from ELVs may substitute virgin plastic in applications outside the automobile industry where the weight or volume does not influence the performance of the plastic product.

Case 1 is not considered in this study as the study does not focus on detailed questions regarding material properties. Case 2 is the underlying definition in this study. Cases 2 and 4 lead to the same results. Case 3 and Case 5 will be discussed later.

Case 2 was selected as the base case in this study. It is described as "open-loop" because it is assumed that recycled plastic will be used in applications with lower mechanical performance. So it is not "closed-loop" but the primary market for recycled material from ELVs is seen as automobile applications. Because recycling activities are widespread and the market for recycled material is limited, the primary target for ELV recycled materials is the automobile sector.

Whether there is the opportunity to satisfy other markets (Case 4) or not, the key element for the environmental performance of this case is a substitution factor of 1. For the environmental assessment, this key element describes the credit this process is given. The credit for virgin material dominates the environmental result. The highest possible credit is attributed to the recycling process if a substitution factor of 1 is applied. Therefore this assumption is very optimistic.

In Case 2 or 4 the environmental assessment of mechanical recycling represents the best scenario. For the plastic parts considered, the conclusion can be drawn that a part which does not show a better environmental performance than other options under these circumstances has no potential for recycling.

For the cost element the chances of improvement are not easy to estimate. The bigger parts like bumpers are dismantled in a straightforward manner and the opportunity for reducing the estimated dismantling cost is estimated to be low. For the smaller parts, which have to be dismantled from assemblies such as the headlamp lenses or the air duct, a reduction potential is possible if the other parts in the assembly are also recycled and the dismantling costs are shared. But even under these circumstances the cost reduction is limited. Further improvement may be possible if the dismantling step can be avoided (see Galloo process below).

In any case, the amount of ELV's recycled material, which can be feed in automobile application, is limited due to the decrease in mechanical properties. The estimation of the market potential was not subject of this study.

Case 3 describes a scenario in which recycled material replaces virgin material even if a weight increase is necessary to compensate reduced specific mechanical properties. This scenario would allow to feed a higher portion of recycled material into automotive applications. Negative in this scenario would be the higher weight of the applications and consequently a higher weight of the car, which leads to a higher fuel consumption during the use phase. The next figures illustrate the effect of higher fuel consumption due to a higher weight of the application on behalf of the bumper. Inside the known portfolio of the bumper (chapter 7.2), the mechanical recycling is embedded[34] with a substitution factor of 0.98 and 0.95 as sensitivity data.

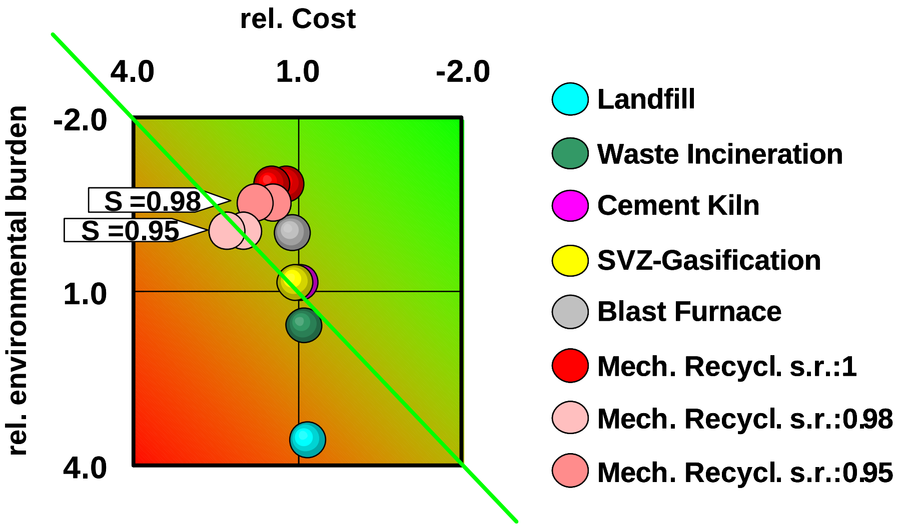

Figure 8.1 Eco-efficiency analysis for bumper including sensitivity data for a substitution factor lower than 1. Sensitivity data includes additional impact for use phase from overweight.

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[34] This sensitivity data is transferred to the existing portfolio but the data is not part of the average.

The sensitivity scenario is calculated by adding the additional impacts due to higher weight in the use phase:

1. In the existing data set (chapter 7.2) the credits for virgin plastic is changed according to the substitution factor. In parallel to the reduced environmental credits, the revenues for recycled material are reduced.
2. The additional impacts for the categories energy, resources and emissions are calculated according to the algorithm in chapter 5.5 resulting from higher fuel consumption due to the additional weight according to the substitution factor.
3. The impact categories risk potential and toxic potential are not changed.
4. Additional cost for higher fuel consumption is included according to the higher substitution factor.

The figure shows the drastic influence of higher weight in automobile applications. Even small additional weight causes a significant reduction in environmental performance. Together with a cost increase, the eco-efficiency gets poor. With a substitution factor of app. 0.98, the eco-efficiency performance of the “minimum-cost” option has to be assessed equivalent to the best recovery option. At this stage, the better environmental performance is outbalanced by the higher cost in comparison of mechanical recycling with the best energy recovery option. Further on, with a substitution factor of app. 0.95, even the environmental performance has no more advantage in comparison to the energy recovery options.

Taking into account that the introduction of the use phase is covering only certain categories and therefore stays rudimental, the signal of this sensitivity analysis is clear. A small reduction in substitution factor in automotive recycling of plastic have a drastic negative influence on the eco-efficiency as well as on the single environmental performance. The potential of mechanical recycling is drastically reduced if the substitution factor is only slightly smaller than 1. This results sound astonishing but a substitution factor of 0.95 means app. 6% higher weight. In this term, the sensitivity analysis is supported by the LCA “total life” in chapter 5.5. The high influence of the use-phase for nearly all categories in the LCA part is reflected by the sensitivity analysis.

Case 5 describes a “open-loop” non-automotive recycling strategy. If the weight or volume has such a drastic impact on the assessment, it is reasonable to look for applications where weight or volume is not important.

The next figures illustrate the effect of a lower substitution factor for the example of the bumper. Inside the known portfolio of the bumper (chapter 7.2), the sensitivity calculations for mechanical recycling are embedded[35] with a substitution factor of 0.8 and 0.6.

The sensitivity scenario is calculated by reducing the credits for virgin plastic according to the substitution factor. In parallel to the reduced environmental credits, the revenues for recycled material are reduced.

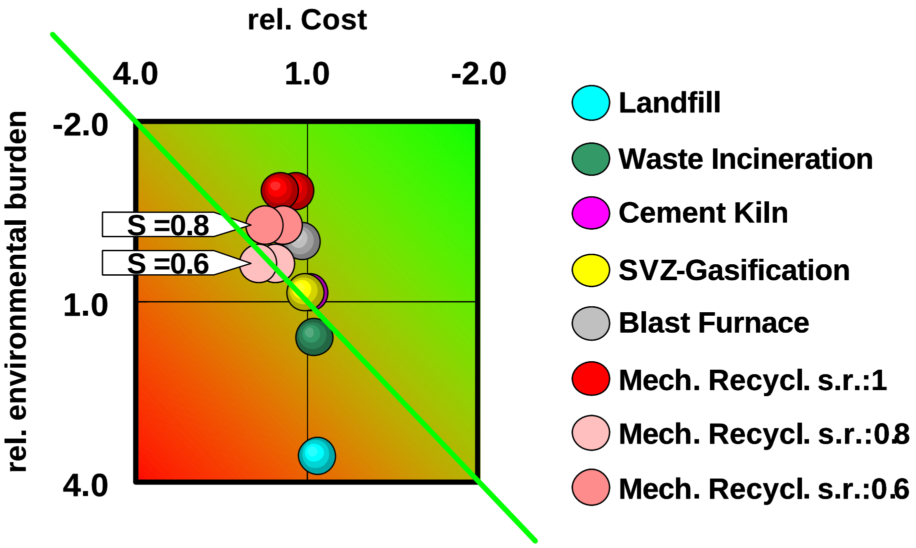

Figure 8.2 Sensitivity analysis for the substitution factor for "open-loop" non automotive application for the example bumper.

The figure shows clearly the impact of the substitution factor on the results. The lower the substitution factor the poorer the eco-efficiency performance. But the change in substitution factor has by far not such a drastic impact as have been noticed for the automotive applications. In terms of eco-efficiency, the mechanical recycling with minimum cost has to be assessed equal in comparison to the best energy recovery option at a substitution factor of 0.8. In terms of environmental performance the mechanical recycling with a substitution factor of 0.6 is poorer then the blast furnace but still better then the other energy recovery option. This sensitivity analysis depicts that there is an advantage for mechanical recycling in non-automotive applications.

8.1.1 Bumper: alternative process steps

The base case for the bumper scenario on mechanical recycling was derived from existing recycling activities. It includes the process steps dismantling and processing. Compounding was not done; the recycled material is used on-site.

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[35] This sensitivity data is transferred to the existing portfolio but the data is not part of the average.

8.1.1.1 Bumper recycling including compounding

Because the market for not-compounded recycled material may be limited, the eco-efficiency of bumper mechanical recycling including the compounding step was analysed. The compounding step causes mainly additional cost. Further on, the compounding step needs heat and electricity.

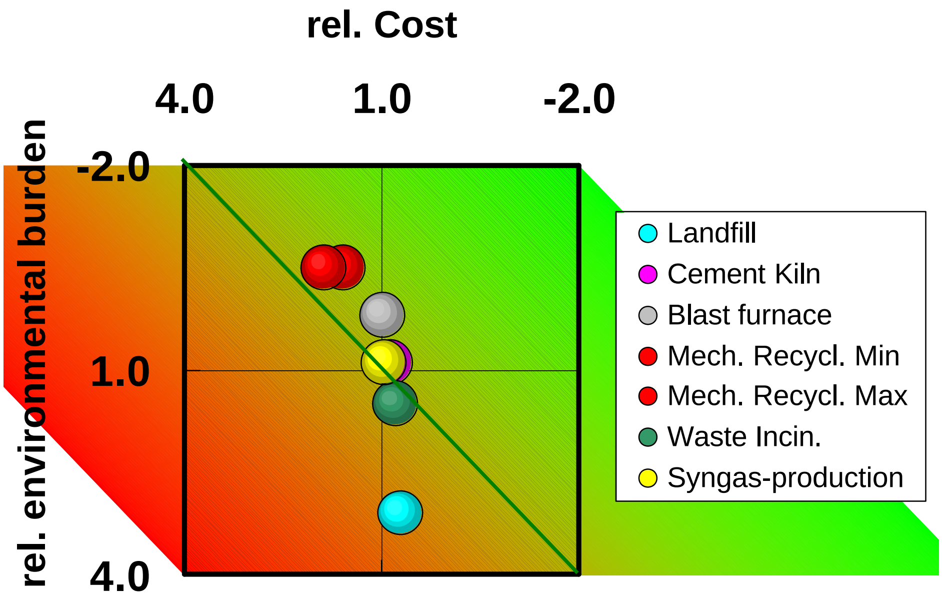

Figure 8.3 Sensitivity for the eco-efficiency analysis on bumper mechanical recycling including compounding.

In comparison to the eco-efficiency of the base case (see chapter 7.2), the figure above shows a small reduction in eco-efficiency of mechanical recycling including compounding. Additional cost and higher environmental burden shift the balls towards the diagonal and becomes equivalent with blast furnace. Nevertheless the assessment of mechanical recycling stays nearly the same. Together with the blast furnace, it is still an eco-efficient option in comparison to the other energy recovery options.

8.1.1.2 Galloo process

The main cost driver for mechanical recycling is dismantling, especially for smaller parts. A way to overcome this costly process is to extract the plastic material from the fluff fraction of the shredder. This approach would use the innovation from post consumer plastic recycling.

One company active in this field is Galloo of France/Belgium. It is operating a pilot plant in connection with a conventional shredder. Galloo has wide experience in the field of plastic recycling. The total design is still under development and therefore details are confidential. The main process steps are:

1. As for the other options the ELV goes to the shredder and the plastic parts remain in the light fraction (fluff).
2. The fluff is pre-treated and the polyolefin's (PP and PE) are separated by flotation. PP and PE have a lower density than water and the other plastics so they can be separated.
3. The PP/PE fraction is then further processed and co-compounded with post-industrial plastic and additives.
4. The compounded material may be used partly in automotive application.
5. The substitution factor is assumed to be 1.
6. All data by Gallo are classified as preliminary data.

The target plastic material is polypropylene (PP) without any filler as filler change the density. Small amounts of polyethylene (PE) come with the PP. PE can be co-compounded with PP to a certain extend.

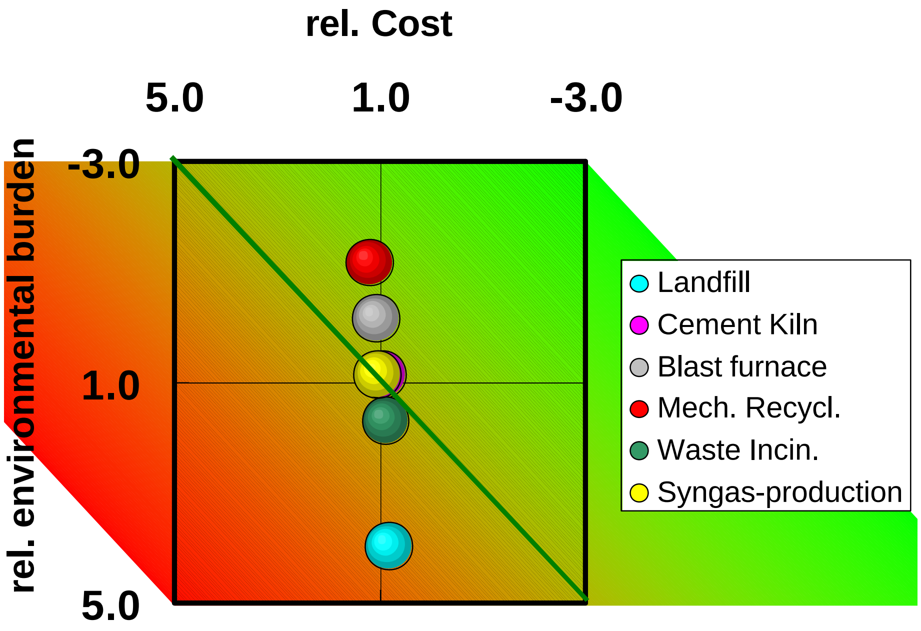

Figure 8.4 Sensitivity for the eco-efficiency analysis on bumper mechanical recycling, Galloo process.

As the bumper is the only part considered, which is made of the same material as Galloo's target plastic, the bumper is taken as reference part for the Galloo process.

The Galloo process exhibits a similar good eco-efficiency as the base case for bumpers. The costs for the Galloo process are of the same order as the "minimum option" for mechanical recycling in the base case. The environmental burden of the Gallo process is somewhat higher and comparable with the mechanical recycling excluding compounding. As the base case of bumper mechanical recycling is the case with the best eco-efficiency performance of all plastic parts considered, the Gallo process looks very promising. The Galloo process avoids the costly dismantling step and therefore the performance of the Galloo process is valid for other smaller PP parts too. For these parts, a change from mechanical recycling with dismantling to mechanical recycling with the Galloo process would mean a drastic increase in eco-efficiency.

8.1.2 Seat Cushions: substitution factor

Seat cushions have been balanced in the main part of the study as non-automotive mechanical recycling. This is done in practise but the market is very limited. If a higher amount of recycled plastic occurs the material has to go to other applications with lower substitution factors.

The sensitivity analysis is performed only for the mechanical recycling. The other options are not changed. In the base scenario (chapter 7.1), the seat cushions are dismantled, metals and sensors are separated and the material is washed and further processed (rebond). This PUR material is introduced in an existing recycling pathway where the PUR material is used as carpet underlay in USA. This market is small and the material has to face competition from other sources, mainly from PUR post-industrial waste. For this application a substitution factor of 1 is estimated. The recycling may be classified as "open-loop" non-automotive recycling.

An alternative way is the production of new seat cushions. After the processing of the dismantled material, new seat foams/cushions can be produced but with higher density. Therefore the substitution factor is estimated to be 0.65.

According to the system boundaries, two changes are introduced in the balance for mechanical recycling. First, the benefit for saving virgin material are lowered with respect to the substitution factor and second, the corresponding cost benefit are estimated accordingly. No impact from a higher weight of the cars as additional fuel consumption is included. So the sensitivity analysis refers to a "open-loop" application. In an automobile application the use phase has to integrated making the environmental performance even worse.

The result is shown in the next figure.

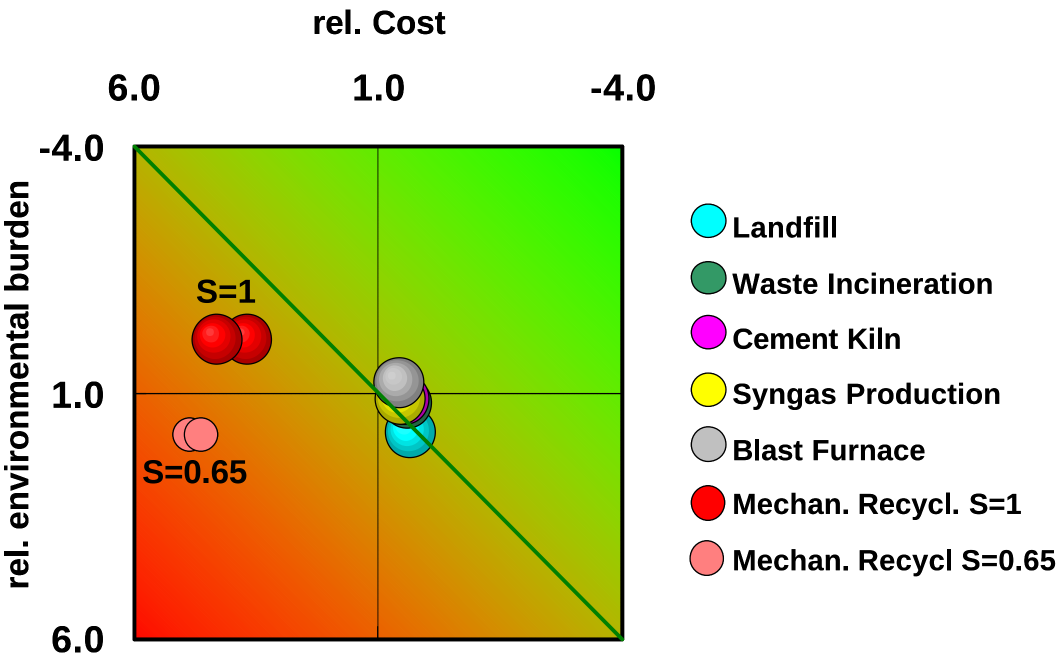

Figure 8.5 Sensitivity analysis for seat cushions with a substitution factor of 0.65.

The eco-efficiency is significant lower for mechanical recycling with a substitution factor of 0.65. It appears to be not only the least eco-efficient option now but also the option with the highest environmental burden.

8.2 Influence of Risk potential and Toxic potential

The categories risk potential and toxic potential are not included in the LCA part. Both categories are developed in a semi-quantitative way. Therefore both are covered in the eco-efficiency part. In this sensitivity analysis the influence of the toxic and risk potential on the total results should be discussed.

The quantification of qualitative aspects can only be done by expert judgement. The aspects listed under both categories serve as a framework or a to-do list. The framework has been mainly established by BASF and covers the main points of interest. Working with the framework guaranty coverage of main aspects. The first result of the work with the framework is that there is no severe aspect, which would influence the overall assessment of one option.

Nevertheless the LCA data and the risk- and toxic potential are summed up to a one-point assessment but from their origin, the data is asymmetric and of different quality. The influence of the risk- and toxic potential is shown in the next figure. For bumpers, the original figure including the risk- and toxic potential is compared with two portfolios:

1. "Toxic potential = 1" + "risk potential =1", For all options the toxic potential and the risk potential is equally one. They are included in the total environmental burden as an off-set.
2. "No toxic potential + risk potential included": For all options the toxic potential and the risk potential is taken out of the sum for the environmental burden.

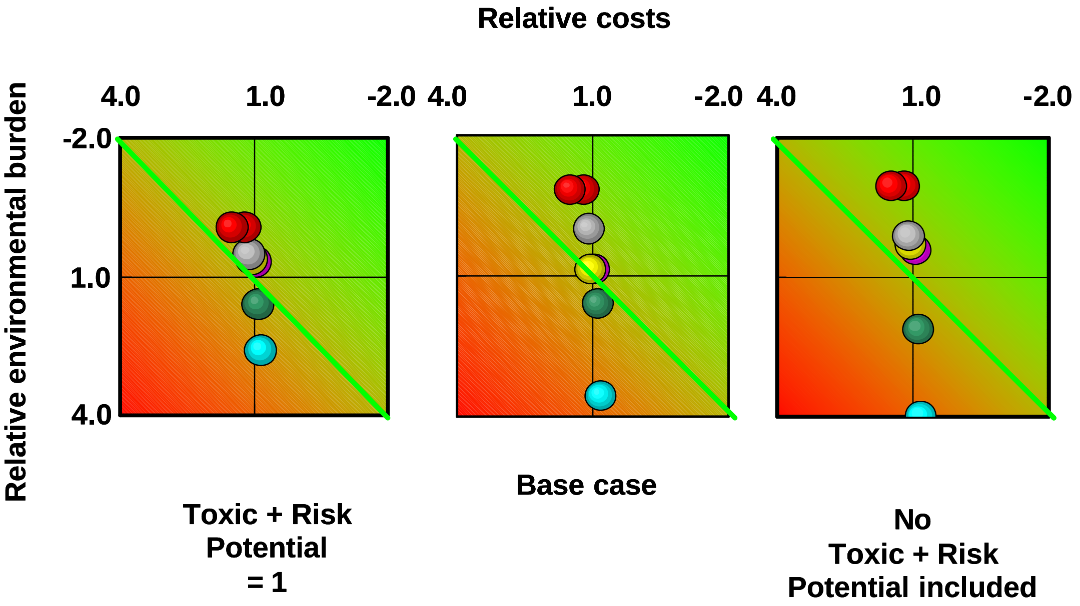

Figure 8.6 Comparison of the eco-efficiency with and without the influence of risk- and toxic potential for the example bumper.

The figure shows that the influence of the risk- and toxic potential. The shape of the figure remains very similar for all three figures. If the toxic potential and risk potential is set one, the figure becomes condensed. If toxic potential and risk potential is not included the figure stretches along the y-axis. The ratio of x-axis and y-axis is determined by the E/C ratio (see chapter 6). The influence of the environmental burden to the E/C ratio is limited to the categories resources, energy and emission. Toxic potential and risk potential is not included. So the E/C ratio and therefore the ratio of x-axis and y-axis is the same for all three figures.

In the left hand case, the toxic potential and risk potential is one for all options. Therefore 30% of the result influencing the environmental burden is the same. Because the **relative** environmental burden is displayed, the difference between the options becomes smaller. The opposite is with the right hand figure, where toxic potential and risk potential is excluded. The differences between the options for the categories resources, energy and emissions become **relatively** more important and this leads to an amplifying of the LCA results. Some minor effects occur in the relative distance between the options. The judgement on risk potential and toxic potential for mechanical recycling is going parallel to the LCA results and reflects the energy and resource conservation with lower and therefore low risk energy and resource flows. In the landfill options, the containment of energy- and resource streams is the underlying reason for both, poor LCA performance as well as high risk due to high stocks.

In case of the other plastic parts the sensitivity analysis on the toxic potential and risk potential leads to similar results:

1. For headlamp lens, airduct and mirror housing no changes in the portfolio can be seen. The relative differences in the environmental burdens are very small because the hugh differences in costs determine the portfolio.
2. The portfolio of the intake manifold and the seat cushions show only very small differences on the influence of the toxic potential and risk potential. The reason is the very condensed environmental axis.
3. The wash-liquid tank exhibits the same changes as the bumper eco-efficiency portfolio. The differences in the “blast furnace”, “cement kiln” and “syngas production” options disappear. All three show a better eco-efficiency then mechanical recycling as they do in the original portfolio. The “waste combustion” option is equivalent to the mechanical recycling if toxic potential and risk potential is included. If toxic potential and risk potential is excluded the “waste combustion” gets worse.

In total the sensitivity analysis on the influence of toxic potential and risk potential shows, that the integration of both has only limited impact on the results. Minor changes occur for the energy recovery options. “Blast furnace” and “waste combustion” are downgraded while “cement kiln” and “syngas production” are upgraded. In principle, the assessment does not change fundamentally.

8.3 General Conclusions and Outlook

In this study the recovery options for seven plastic parts have been explored and assessed in terms of eco-efficiency. It should cover Western Europe. Although the data mainly based on German figures, it is assessed to reflect the average European situation. No regional differences have been taken into account. The parts show a wide variety in their results. Nevertheless some common main conclusions can be drawn from the results:

1. The energy / feedstock recovery options (blast furnace, cement kiln and syngas production) show a close environmental and cost performance. In terms of eco-efficiency they all score very similar. Except for the mechanical recycling of bumpers, the options score better or equivalent in terms of eco-efficiency.

2. The mechanical recycling option shows a big variation, mainly in costs. Mechanical recycling can compete with energy recycling options only if big, easy to dismantle parts are considered.
3. Landfill always appears as worst solution in the base cases and
4. Waste combustion generally shows a worse performance than the other energy / feedstock recovery options.

In the sensitivity analysis, it is shown, that

1. Mechanical recycling strongly depends on the substitution rate (virgin material to recyclate). In the base case a substitution rate of 1 is considered. Taking into account a substitution rate of 0.98 in a “closed-loop” automotive recycling, the mechanical recycling score equivalent to the energy recycling options due to the higher weight and its impact during the use phase. A “closed-loop” automotive recycling therefore may be counterproductive.
2. If recyclates are used in “open-loop” application in which weight has no impact on the use phase, a substitution rate of 0.8 leads to similar scores as the energy recovery options.

Additional to the limitation within the scope of the LCA, the interpretation of the eco-efficiency results should reflect that:

1. The eco-efficiency method is a new tool and interpretation should be done carefully.
2. The eco-efficiency method includes an aggregation step and thus the results are method-dependent. Other aggregation method may lead to other results.
3. Beside landfill and waste combustion, all other options are future processes. Their environmental performance are deduced from small scale operations or operations with similar materials. Nevertheless, especially the costs (gate fees) for energy / feedstock recovery options are estimates and differences between options as well as differences for the different kind of plastics might erase even the average figures hold.
4. Beside landfill and waste combustion, no capacity-driven or market-driven drawbacks have been implemented in the study. Syngas production capacity is low. Cement kiln and blast furnace need intensive mechanical processing. The market for recyclates are still small and the development of this market segment is unknown if the amount of recyclates may increase in the future. This limitation may have an important impact on the cost analysis.

5. Further impacts on the availability of recycling capacity from recycling activities for other products have not taken into account. This may change the fundamental question of this report: from “which option is best for ELV plastic part?” to “which type of waste is best for which option?”

Additional to this study, some aspects have been identified to contribute to the knowledge of future recycling and recovery of ELV plastic parts and may be subject for future studies:

1. Prospective economic study, making assumptions on the potential market for recycled plastic, the capacity for recycling operations and the capacity for the other recovery options in Europe especially with regard to the new EU member states.
2. Reconsideration of the results within 5 years, taking into account the evolution of techniques and ELV composition.

9 Critical Review Report

This project was completed by Öko-Institut and BASF for the APME. It investigates the costs and environmental balances of different recovery options for several plastic automotive parts from End of Life Vehicles (ELVs).

The report is divided into two parts:

- the first part is dedicated to the LCA and the cost inventory of the different routes under study; and
- the second part is dedicated to the analysis of the eco-efficiency of the options under study.

The critical review panel reviewed the entire document, although only the LCA part was considered in reference to the ISO 14040 standards.

Function of the Critical Review

LCA should be performed according to standards ISO 14040 and following. According to the ISO 14040 standard, a critical review process is necessary if LCA results are used for comparative assertions which are intended to be disclosed to the public. This is valid for the LCA on hand.

According to ISO 14040 the critical review process shall ensure that:

- the methods used to carry out LCA are consistent with the International Standard,
- the methods used to carry out LCA are scientifically and technically valid,
- the data used are appropriate and reasonable in relation to the goal of the study,
- the interpretations reflect the limitations and the goal of the study,
- the study report is transparent and consistent.

Since the International Standard does not specify requirements on the goals or uses of LCA, a critical review can neither verify nor validate the goals that are chosen for an LCA, or the uses to which LCA results are applied.

Members of the critical review panel were Helene Teulon (chairperson), Roland Hischier, and Roberto Zoboli.

Three meetings were hold gathering the critical review panel, the commissioner and the authors of the study. Intermediate documents were exchanged and several phone conferences were conducted to solve points of concerns.

Goal and Scope

The goal and scope of the project are clearly displayed in the report. It is stated that this project aims at assessing the "environmental performance of different recycling/recovery options for plastic parts in end of life vehicles", "for benchmarking the different options" and "internal learning".

The limitations are also clearly mentioned (see below).

The temporal scope of the study is between 2005 and 2010.

Methodology and Data

The methodology and the assumptions made along the project are logical and scientifically valid. They are consistent with the goal and scope of the project.

The selection of the parts was argued in a separate report and makes sense to the panelists.

The approach for the selection of data is a pragmatic approach: most data are representative of European Northern countries, even if the geographical scope of the project is Western Europe. The data are characterized in Table 5.2 page 36.

This is consistent with the goal and scope of the project.

The reviewers were provided with calculation spreadsheets in electronic format for a more efficient review process. Random checking was completed. The calculation methods that were investigated are valid.

Limitations

The main limitations of the approach are displayed in the body of the report. They mainly concern:

- the selected approach for this first study does not take into account the evolution of the waste treatment techniques over the next 10 years and the possible changes in the composition of ELVs,
- nor are the future capacities for waste treatment estimated,
- besides, the data quality is not fully homogeneous over the different options under study: since recycling operations are still at the pilot level for numerous plastic types, data had to be extrapolated, based on expert judgement.
- the assumption of a substitution rate of 1 for recycled plastics,
- the potential influence of flows of plastic waste coming from other industries, that would change the economics of the recycling/recovery options under study, or offer new opportunities of recovery.

- the assumption on a non-saturated market for recycled plastics.

The panelists would like to underline that the use of a weighting method, including an innovative semi-quantitative method for estimating risk and toxicology concerns, could also be considered as a limitation of the approach.

Eco-efficiency Study

The calculations for building the eco-efficiency portfolio are clearly displayed in the report and the annex 2. The transparency of the calculation was greatly improved along the critical review process. The valuable work that was provided should be useful for future projects too.

The calculations are consistent, although they could be simplified. Some of the calculation steps can be discussed, as for instance the selection of a geometric average between societal factors and environmental relevance to build the environmental weighting indicators. However, the choice of the authors of the study is clear and transparent.

The proposed approach to deal with risk and toxicology concerns is innovative and interesting. However, the mixing of reliable quantitative LCA data with qualitative risk and toxicology data might reduce the reliability of the conclusions. The authors present a sensitivity analysis where the risk and toxicology data are removed. The panelists suggest that the report could have been displayed the other way round, with LCA data as the base case and risk and toxicology as a sensitivity analysis. Nevertheless, the panelists agree that the approach is valuable and should be developed in the future, and supported by quantitative data.

The sensitivity analysis are particularly interesting:

- They demonstrate and quantify the importance of the substitution rate, and the related influence of the product in which the recycled plastics are used,
- They underline the potential benefits of an industrial recycling process, where the parts do not have to be dismantled. The sensitivity analysis on the Galloo process was performed on the bumper, but the results would have been much more demonstrative on a smaller part with higher dismantling costs.

Results and Conclusions

The results summarized in the executive summary truly reflect the content of the project.

As for any aggregation method, the results of the eco-efficiency portfolio are method-dependent. During the critical review process, another eco-efficiency method was tested, using a different weighting method and not taking into account risk and toxicity. Significant differences in the conclusions were found for some of the parts.

This means that the results for individual parts might not be of general interest. But some general valuable results are drawn from the study in the conclusion:

- The recovery through blast furnace, cement kiln and syngas often show a close environmental and cost performance – the cost performance might be linked to the imperfect modeling of costs through gate fees though,
- The recycling option shows big variations in costs and environmental performance, with the part considered (size, dismantling costs, type of plastic),
- Landfill always appears as the worst solution from an environmental point of view, and
- Incineration generally shows a worse performance than blast furnace, cement kiln and syngas.

The authors very relevantly underline in the conclusion that a further investigation could focus on economic factors such a the available recycling operation capacities and the available markets for recycled materials, taking into account other plastic waste flows than plastics from ELVs.

Report, Compliance with ISO 14040ff

The overall report is consistent and transparent.

The LCA part complies in general with the recommendations of the ISO14040 and following regarding data, methodology and reporting. For a better compliance, some intermediate conclusions could have been drawn from the LCA study on the relative environmental performance of different recycling/recovery options for each part under study, so that the first part of the report includes an interpretation phase.

In the second part of the report, a weighting method is used to combine the different environmental burdens into a single note, which is not consistent with ISO 14040 recommendations.

The mandatory statements requested by standard ISO 14042 (10.2.3 f) regarding the use of a weighting methods are included in the report (§5.1.3.3).

Overall Conclusion

The report is very dense, it is however transparent and displays clear objectives. The development of the methodology is logical and scientifically valid, the approach for the selection of data is pragmatic, they are both consistent with the goal and scope of the project. A relevant set of parts was selected for the project.

Even if individual conclusions for ELVs' parts might change with the method chosen to calculate eco-efficiency, relevant conclusions are drawn from the study.

The LCA part of the project was in general conducted in compliance with the recommendations of the ISO 14040ff standards.

The critical review process was very constructive, significant efforts were successfully dedicated to the improvement of the project and the report along this process.

Page per Page Comments

N°	Page	Topic	Comment
1	79	Normalization	Instead of including the Max of the options in the definition of the relevance factors, the following definition could have been used: $\mathrm{Re}\,levance_{env} = \dfrac{1}{Total\ Environemntal\ \mathrm{Im}\,pact\ in\ Europe}$ It would make the calculation easier and clearer. It such a definition of the relevance was used, the ratio would be "the contribution of the considered process to the total environmental load in the EU". Another advantage of this definition is that the results does not change with the set of options under study.
2	80 and Annex 2	Normalisation of environmental effects	For the weighting factors, a geometric average was selected. The reasons for this choice are not really convincing : a sum of 100% could be reached with other methods (argument 1), and arguments 2 and 3 on page 80 are just one argument, it says that the weighting amplifies the differences. Having the weighting factors changing with each set of data does not seem to be an advantage, but a drawback of the method.
3	91	Economic weighting factor	Same remark as for environmental weighting: including the Max of the costs of the different options under study makes the relevance cost factor dependant on the set of options, which appears as a drawback. The following definition for the cost relevance could be used instead: $\mathrm{Re}\,levance_{Cost} = \dfrac{1}{Sales\ of\ \ total\ manuf.\ Industry\ in\ Europe}$
4	91,92	Weighting of ecology and economy	The whole section 6.4.2 is not fully clear. The meaning of the diagonal is asserted but the logical demonstration is not fully convincing.
5	112	Galloo Mechanical Recycling	It could be mentioned that the Galloo process is likely to show eventual productivity gains, whereas the dismantling steps quickly reach their productivity limit.
6	Annex p. 20	Portfolio calculation	The calculation process was made fully transparent, the reason for performing each calculation step could be further developed.

10 Glossary

Dismantling efficiency	Mass of dismantled part per time needed for dismantling. Unit: grams per second.
Dismantling information	All information required for the correct and environmentally sound treatment of end-of life vehicles. It shall be made available to authorised treatment facilities by vehicle manufacturers and component producers in the form of manuals or by means of electronic media (e.g. CD-ROM, on-line services)
Disposal	Any of the applicable operations provided for in Annex IIA to Directive 75/442/EEC
ELV	End-of-Life Vehicle
End-of life vehicle	A vehicle which is waste within the meaning of Article 1(a) of Directive 75/442/EEC
Energy recovery	The use of combustible waste as a means to generate energy through direct combustion with or without other waste but with recovery of the heat
Hazardous substance	Any substance which is considered to be dangerous under Directive 67/548/EEC
IDIS	Database containing information about dismantling [IDIS 2000]
LCA	LCA = Life Cycle Assessment
MSWC	Municipal Waste Combustion
Prevention	Measures aiming at the reduction of the quantity and the harmfulness for the environment of end-of life vehicles, their materials and substances
Producer	The vehicle manufacturer or the professional importer of a vehicle into a Member State
Recovery	Any of the applicable operations provided for in Annex IIB to Directive 75/442/EEC
Recycling	The reprocessing in a production process of the waste materials for the original purpose or for other purposes but excluding energy recovery.
Reuse	Any operation by which components of end-of life vehicles are used for the same purpose for which they were conceived

Shredder	Any device used for tearing into pieces or fragmenting end-of life vehicles, including for the purpose of obtaining directly reusable metal scrap
Treatment	Any activity after the end-of life vehicle has been handed over to a facility for depollution, dismantling, shearing, shredding, recovery or preparation for disposal of the shredder wastes, and any other operation carried out for the recovery and/or disposal of the end-of life vehicle and its components

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